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DESALINATION OF BRACKISH WATERS FOR PRODUCTION OF FRESH WATER FOR DOMESTIC AND AGRICULTURAL WATER SUPPLIES IN SELECTED COUNTRIES OF THE ESCWA REGION

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ABBREVIATIONS

BD	Bahrain dinar
Br	Brackish
Ca	Calcium
CL	Chlorine; Chloride
DH	Dharham
EC	Electroconductivity
ED	Electrodialysis
EDR	Electrodialysis reversal
GPD	Gallons per day
GW	Ground water
g.l.	ground level
H	High
h	hour
HCO_3	Bicarbonate
L	Low
LC	Local currency
K	Potasium
kW	Kilowatt
KD	Kuwaiti dinar
km^2	Square kilometre
km^3	Cubic kilometre
M	Million
MCM	Million cubic metres
Mm^3/d	Millions of cubic metres per day
Mg	Magnesium
mg/l	Milligrams per litre
Mgd	Millions of gallons per day
MIgd	Millions of imperial gallons per day
MSF	Multi-stage flash method
m	metre
m^3/d	Cubic metres per day
mm	Millimetre
mm/annum	Millimetres per annum
mm/yr	Millimetres per year
MW	Megawatt
Na	Sodium
PV	Photovoltaics
ppm	Parts per million
QR	Qatar riyal
O and M	Operations and maintenance
RO	Rial Omani
ro	Reverse osmosis
TDS	Total dissolved solids
SO_4	Sulphate
SR	Saudi Arabian riyal
SW	Sea water
WMO	World Meteorological Organization
WHO	World Health Organization
$US	United States dollar
WECS	Wind energy conversion system

INTRODUCTION

Basic considerations

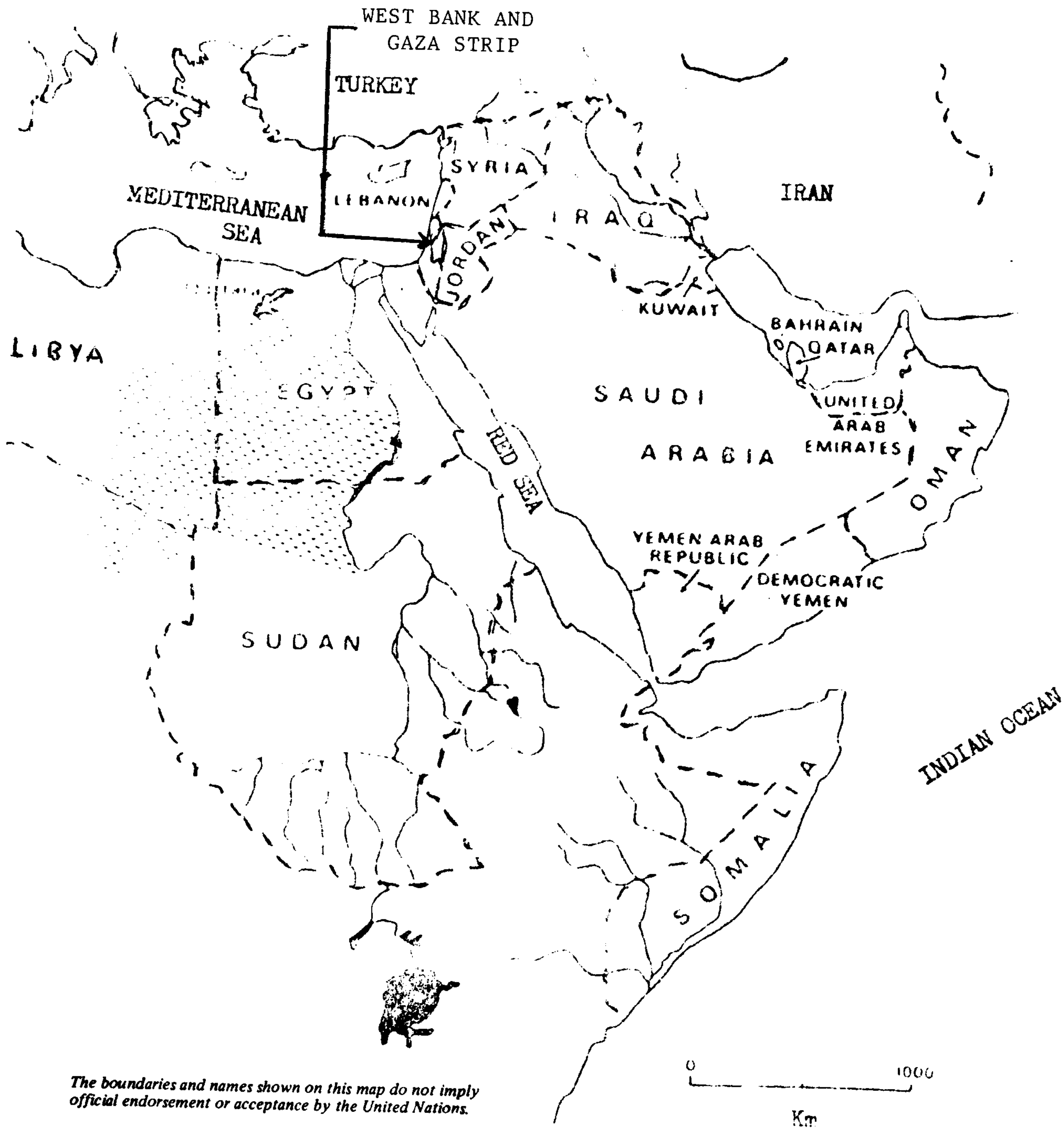
Climatic conditions, characterized by relatively low, unpredictable and variable rainfall and high evaporation rates, partly explain why water scarcity has become a major development constraint in the fast-growing ESCWA region (see map 1). Hence ESCWA countries have made efforts to develop much-needed water systems where a comprehensive approach to planning and development of water resources is considerably lacking, in order to meet the growing demand for various uses of water, as is explained in table 1.

Until the end of the Second World War, the rate of land and water development in the ESCWA region was very low. Rapid development started in the 1950s, and gained momentum in the following two decades. Many countries in the region introduced national development plans in which the water sector, and particularly the development of conventional water resources, was given top priority. Consequently, easily accessible water resources such as river flows and shallow ground water of good quality are now being utilized.

At present great efforts are being made in the region to develop additional water resources. In all large river basins, major storage reservoirs have been built, or are under construction (the Euphrates, the Tigris and the Nile). In other parts of the region (the Syrian Arab Republic, Jordan and Saudi Arabia), a number of smaller dams are at different stages of planning or execution. The two Yemens are planning to develop water supply and irrigation schemes in order to optimize the seasonal flood waters of their wadis and ground-water reservoirs in the alluvial plains of the wadis. The huge ground-water basins discovered so far (Egypt, Saudi Arabia and the Gulf States) are being developed. Table 2 indicates the relative use of conventional water resources in the different ESCWA countries.

Throughout the 1970s, rapid socio-economic development has given cause for concern in the formulation of national development plans in ESCWA countries. It is becoming more and more evident to decision makers in the region that conventional water resources and surface and ground water, constitute potential national assets that are vital to almost every phase of the economy. Neglect or misuse of these valuable and scarce resources can adversely affect the prosperity of inhabitants and hinder the overall economic development of the region. Hence, decision makers are becoming increasingly concerned about devising ways to optimise the use of available water resources by non-conventional means, such as brackish and sea water desalination and the treatment of sewage effluent in order to meet the excessive demand for water, as is projected in table 3. This is the case with ESCWA countries in general, and especially with Gulf Co-operation Council (GCC) countries, which are heavily dependent on non-conventional water for their water supply, particularly on expensive brackish and sea water desalination. Table 2 indicates the present relative use of non-conventional water resources in different member countries.

Map 1. Location map of the ESCWA region



The boundaries and names shown on this map do not imply official endorsement or acceptance by the United Nations.

Table 1. Projected water demand in the ESCWA region

(Mm^3)

		Year		
		1985	2000	2030
Gulf Countries	Domestic use	1,017	739	4,214
	Industrial use	180	602	2,673
	Agricultural use	21,564	24,919	28,587
Sub-total		22,761	27,260	36,474
Other ESCWA countries	Domestic use	3,273	6,035	16,410
	Industrial use	646	2,038	10,260
	Agricultural uses	63,364	71,842	77,651
Sub-total		71,202	79,915	104,321
Total		93,963	107,175	244,116

Source: Adapted from S. Asa'ad and N. Rufail, "Water resources in the Arab world and their optimum use", paper presented at the Arab Centre for the Study of Arid Zones and Dry Lands - Arab Fund for Economic and Social Development - Kuwait Fund for Arab Economic Development (ACSAD, AFESD, KFEAD) Workshop on Water Resources Utilization in the Arab World, Kuwait 17 to 20 February 1986 (in Arabic).

The water shortage problem in the region, where the known potential supply of fresh water from conventional sources is insufficient to meet demand, could be alleviated through the better utilization of available resources by means of more rational management and priority determination for particular purposes, or the augmentation of these by non-conventional water resources. Under the prevailing economic and technical conditions, sea and brackish water desalination is considered to be a viable means of increasing the supply of fresh water. Hence, desalination offered an expedient solution to help close the gap in areas short of water in oil-producing countries, and in meeting the excessive demand for water over the last decade, as the following figures compiled from different sources show:

Desalination (Mm^3/d)	Bahrain	Iraq	Kuwait	Qatar	Oman	Saudi Arabia
1979	0.030	...	0.470	0.110	0.001	0.640
1984	0.098	0.020	0.970	0.137	0.030	0.140

Note: ... Data not available.

Table 2. Relative present use of conventional water resources in the region

Country or area	Surface water			Ground water			Brackish water				
							Available quantity		Uses		
	High	Medium	Low	High	Medium	Low	High	Low	Direct	Blended with distillate	Desalinated
Bahrain	X	-	-	X	-	-	X	-	X	X	X
Democratic Yemen	-	--	X	X	-	-	X	-	X	-	-
Egypt	X	-	-	-	X	-	-	X	X	-	-
Iraq	X	-	-	-	-	X	-	X	X	-	-
Jordan	-	X	-	X	-	-	X	-	X	-	-
Lebanon	X	-	-	-	X	-	-	X	X	-	
Kuwait	-	-	-	X	-	-	X	-	X	X	X
Qatar	-	-	-	X	-	-	X	-	X	X	X
West Bank and Gaza Strip	-	X	-	X	-	-	X	-	X	-	-
Oman	-	-	X	X	-	-	X	-	X	X	-
Saudi Arabia	-	-	X	X	-	-	X	-	-	X	X
Syrian Arab Republic	-	X	-	X	-	-	X	-	-	-	-
United Arab Emirates	-	-	X	X	-	-	X	-	-	X	X
Yemen	-	-	X	X	-	-	-	X	X	-	-

Source: Data compiled by ESCWA.

Table 3. Present relative use of non-conventional water resources in the region

Country or Area	Sea water desalination			Brackish water desalination			Effluent reuse			Others (water transport, weather modification, etc.)
	High	Medium	Low	High	Medium	Low	High	Medium	Low	
Bahrain	-	X	-	X	-	-	X	-	-	-
Democratic Yemen	-	-	-	-	-	-	-	-	X	-
Egypt	-	-	X	-	-	-	-	X	-	-
Iraq	-	-	-	-	-	X	X	X	-	-
Jordan	-	-	-	-	-	-	-	X	-	-
Lebanon	-	-	-	-	-	-	-	-	-	-
Kuwait	X	-	-	-	-	X	X	-	-	-
Qatar	X	-	-	-	X	-	X	-	-	-
West Bank and Gaza Strip	-	-	-	-	-	-	-	-	-	-
Oman	-	X	-	-	X	-	-	-	-	-
Saudi Arabia	X	-	-	-	X	-	-	X	-	-
Syrian Arab Republic	-	-	-	-	-	-	-	X	-	-
United Arab Emirates	X	-	-	X	-	-	-	X	-	-
Yemen	-	-	-	-	-	-	-	-	X	-

Source: Data compiled by ESCWA.

New techniques developed over the last two decades have enabled many ESCWA countries to assess their water resource potential more accurately, and to introduce more efficient technologies in order to add to these resources by using different desalination processes, so that fresh water can be obtained from brackish water. Such techniques could have a greater impact on future usable water supplies than any of the other technologies that aim at increasing these supplies, such as water harvesting, treated sewage water, weather modification, etc.

The current study will focus on the use of brackish water to supplement existing fresh water supplies in the region, whether for irrigation as in some of the Gulf countries, or, after dilution with better quality water, as in Jordan and the Syrian Arab Republic. Though most of the aspects of the desalination of brackish water are introduced in this study, a discussion of sea water desalination being developed cannot be avoided and considered along with desalinated brackish water as a source of water supply. Research on desalination over the last 30 years has combined both methods, since the object of desalination is to produce fresh potable water.

Objectives and scope of work

In compliance with the Mar del Plata Action Plan of the United Nations Water Conference held in 1977,1/ and in recognition of the importance of water for the economic well-being of people, the United Nations, in General Assembly resolution 35/18, declared the years 1981-1990 to be the International Drinking Water Supply and Sanitation Decade. The current study has been developed in that context. The limited conventional water resources, and the concern that they would fail to meet demand in the long-term led many ESCWA countries to the conclusion that alternative water resources need to be investigated, including the development of non-conventional means. Alternative non-conventional water resources such as the desalination of sea and brackish water and effluent reuse, attract immediate consideration. However, it should be borne in mind that no single non-conventional solution is adequate for all parts of the ESCWA region.

Over the last decade, hydrogeological investigations have established the availability of brackish water in different parts of the ESCWA region. The Natural Resources, Science and Technology Division of the ESCWA secretariat, in compliance with the Mar del Plata Action Plan and the International Drinking Water Supply and Sanitation Decade, therefore, envisaged the present study on the desalination of brackish water for the production of fresh water for domestic and agricultural water supplies in selected countries and areas of the ESCWA region, and in particular the Gulf countries of Bahrain, Kuwait, Qatar, Oman, Saudi Arabia and the United Arab Emirates, which rely heavily on desalinated sea and brackish water for domestic and industrial uses. Hence, the present study will pay special attention to these countries.

1/ Report of the United Nations Water Conference, Mar del Plata, 14 to 25 March 1977 (United Nations publication, Sales No. E.77 II.A.12).

The study reviews desalination technologies, brackish water availability in the region, brackish water desalination activities in the selected member countries, the sources of new and renewable energy applications in desalination, an indicative cost-benefit analysis of brackish water desalination according to different factors (salinity level, project size, etc.); the conclusions and recommendations on the use of brackish water for different purposes are drawn to the attention of member countries.

Involved in the preparation of the study were the following:

(a) A questionnaire covering the main subject areas in the water sector, which was prepared and distributed to concerned officials in member States, the focal points, as well as to United Nations and Arab regional organizations active in the water sector;

(b) Missions to Bahrain, Kuwait, the United Arab Emirates and Oman, in order to collect information and to consult with concerned officials;

(c) The consultation of relevant literature, country reports, papers and documents, which were made available through direct contact and/or correspondence with the concerned government authorities, United Nations specialized agencies and Arab regional organizations;

(d) An analysis and interpretation of the information gathered, after which this study was prepared.

I. DESALINATION

A. Background

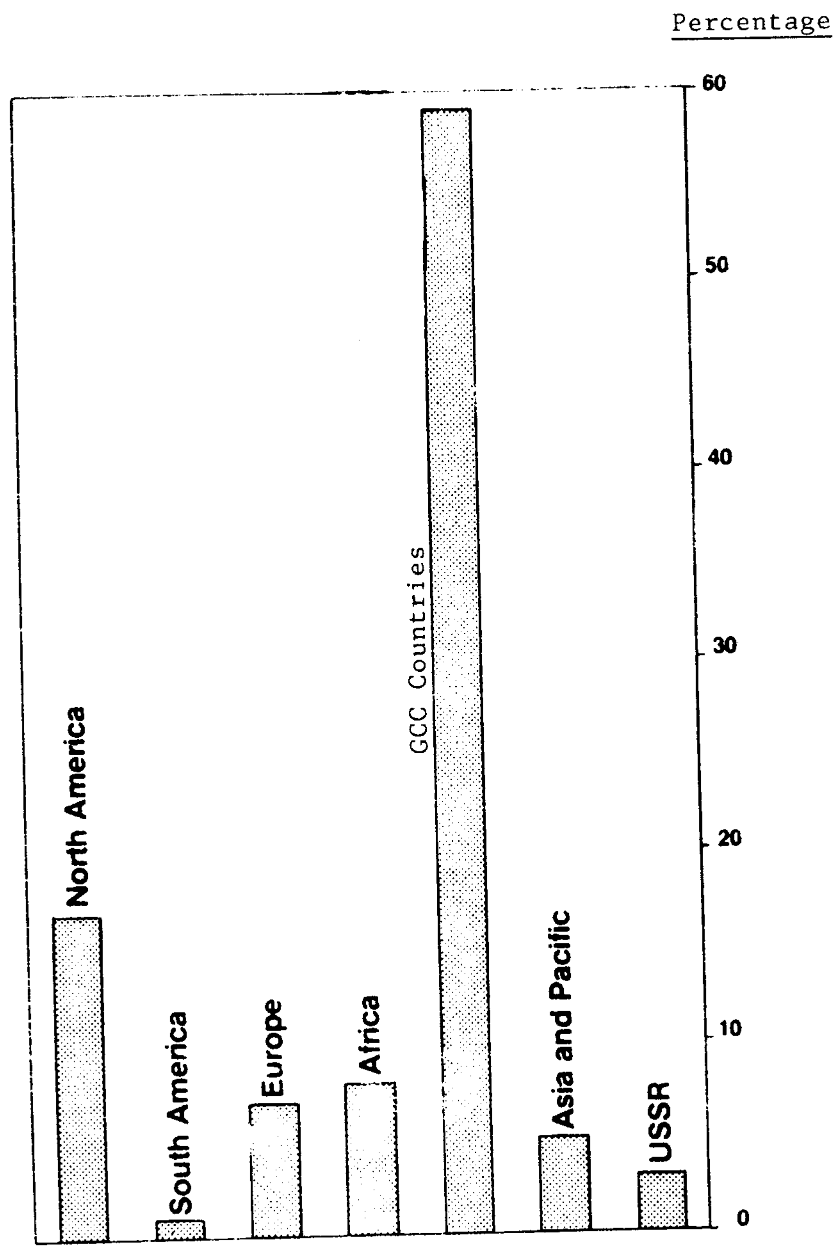
This chapter sheds light on the major desalination processes in use in the ESCWA region: distillation, ED, EDR and RO. Special attention is given to electrodialysis, electrodialysis reversal and reverse osmosis, as these constitute the techniques applicable to brackish water desalination, which is the core of the current study. It is worth mentioning that desalting technology is still in the development stage and that considerable research and work are still required to reduce the cost of desalted water before it can constitute a significant supplement to fresh water resources. The desalination market in the region was very limited until 1973 when the oil-producing member countries decided to meet the increasing demand for water for different uses by constructing huge desalination plants. Hence, the desalination of sea and brackish water now plays an important role in these countries. Therefore it is necessary to determine the state of the art of desalination, as in any developing technology, before deciding on any future course of action.

High levels of salinity in sea and brackish water render them unacceptable for domestic and agricultural use. The concept of desalination is not new, and it has been experimented with and discussed for some time. What is new about desalination is its commercial development and the viability of the desalination technique, which makes desalinated water a reliable non-conventional source. Before the desalinaion industry flourished in the last two decades, small stills had been used to produce fresh water on ships for several centuries and distillation technology was well known in many industries. The cost of distilling sea and brackish water was high, when compared to conventional sources. Egypt was one of the countries that constructed marine-type distillation plants for municipal use in the early 1900s. In 1950, world production was about 10,000 m^3/d in a few scattered land-based desalination plants. In 1985, the world desalination capacity had grown to about 7.5 Mm^3/d. Figure 1 shows the growth in desalination capacity up to 1980 in GCC countries, as compared with other regions in the world.

In the 1950s, desalination distillation was the only viable process. The plants in existence were of the small, multiple-effect type, with capacities of 20 to 60 m^3/d that were used mainly for boiler feed water. In 1952, the United States Government established the Office of Saline Water (OSW), to which the present desalination industry technical basis can be attributed. Also in the United States, the Office of Water Research and Technology (OWRT) spent more than $US 300 million on studies, research and demonstration plants over a period of 30 years. In the mid-1950s the distillation submerged-tube multiple-effect plants were replaced by the distillation multi-stage flash processes that were developed and patented in Scotland, and which currently account for two thirds of world desalination capacity.

In the 1950s, a major technological development took place, by which brackish water was desalinated by electrodialysis. Most units were built and installed in the ESCWA region, but operational problems such as the formation of precipitation in stacks (scaling) have been experienced. In 1953, the basic

Figure 1. Distribution of desalination capacity by region, 1980



Source: United Nations, Department of Technical Co-operation for Development, The Use of Non-Conventional Water Resources in Developing Countries (1985), p. 15 (ST/ESA/149).

principles of RO were demonstrated. Progress was made in the late 1950s when membrance flux, stability and salt rejection improved, making the process commercially viable (1), (2).

Technically speaking, desalination is the process of separating water from salt in a solution. It can be realized using a number of different operations. The techniques that are commonly used today can be grouped according to the processes involved. These are as follows:

1. Processes that use a phase change of water. These are:

(a) Distillation: different techniques are commonly used, mainly to desalt sea water:

(i) Single and multi-stage flash (MSF);

(ii) Multi-effect (ME) distillation, as in horizontal tube multi-effect (HTME) and vertical tube multi-effect (VTME);

(b) Freezing: this is not common in the ESCWA region, as it is not yet economically viable. Typically, the process operates between approximately -50^{o} C (the freezing temperature of sea water) and the ambient air temperature (melting point) in which water separates itself at a higher freezing point by crystallization within a saline solution;

(c) Vapour compression: this is not in common use in the ESCWA countries.

2. Processes utilizing the properties of membranes

These processes are selective transport methods in which salt or solvent is transferred away from the feed solution across some physical barrier, without there being a change in the state of the solvent; this is in contrast to distillation and freezing; which depend on a change in the state of the solvent to bring about the desired separation, which includes:

(a) ED;

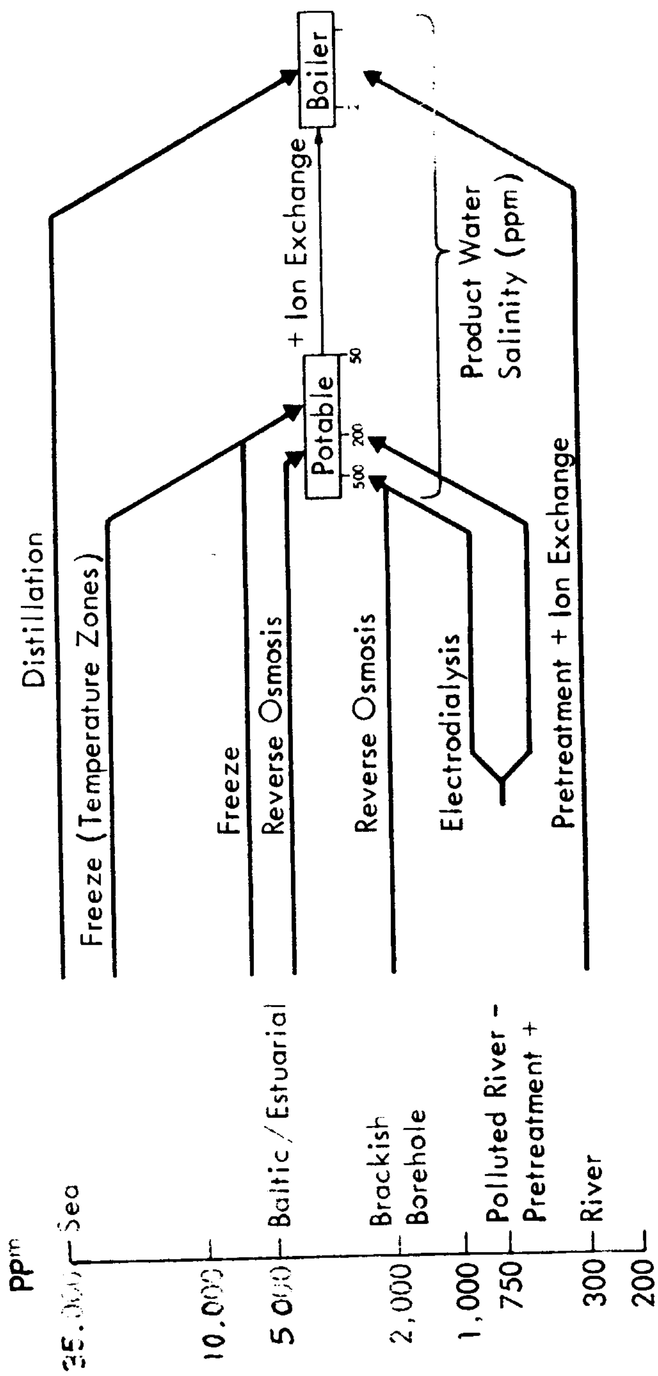
(b) EDR;

(c) RO.

Membrane desalination techniques were first used to desalinate brackish water; later developments in their technology made them economically viable for sea water desalination. In fact, EDR is an improved technology of ED.

Before considering the desalination processes mentioned above, the chemical definition of brackish water with regard to its total dissolved solids content, as compared with other types of water, is shown in figure 2. Water quality standards for both potable and agricultural use are given in order to indicate the water quality requirements of desalinated water.

Figure 2. <u>Feed-water salinity and process applicability</u>



Source: "Solar water desalination", B. H. Khoshaim and J. S. Williamson, eds., Proceedings of the Second SOLERAS Workshop, March 1981, Denver, Colorado, USA, (MRI/SOL-0901), p. 74.

B. Water quality

Brackish water is either plain or difficult. The plain variety is classified as water without any contaminants and toxicants: this is either well water with high TDS that requires desalting for local water shortage, or steam-electric generation return flow water, or brackish water used for drinking water and cleaning. Difficult brackish water is classified as industrial and manufacturing return flow and reuse water, which typically includes toxicants and contaminants in the waste water. The brackish water limit is usually designated as water with total dissolved solids that range from 1,000 ppm to 10,000 ppm.

Hence, the key to desalination is the water quality in terms of chemical and organic constituents. Therefore, different types of biological-physical-chemical analyses are always required in order to determine the variation of water quality over time so as to provide adequate data to ensure that raw water treatment will be efficient under all circumstances. In addition, the prevailing environmental conditions should be studied in order to avoid possible incidences of pollution, whether accidental or not, such as oil contamination and the presence of industrial or domestic effluent in the raw water. In this context, it is necessary to refer to the use of the desalinated product in order to specify its quality requirements. Tables 4 and 5 respectively exhibit potable and irrigation water quality requirements in terms of their physical-chemical properties. However, it is common practice that each desalination process is applicable to a certain range of salinity limits, as is indicated in figure 2.

C. Desalination processes

1. Distillation

Water distillation has been known for some time and was originally used on a small scale only for scientific purposes. It is now a common process used in the desalination of sea water and is considered to be a mature technology that is used around the world. Over 55 countries have distillation plants that produce 5.5 Mm^3/d.

By this process the solution is brought to a thermodynamic state in which the more volatile component is separated through evaporation from the less volatile salts. This state can be attained either by raising the temperature of the solution at a constant pressure, or by lowering the pressure at a constant temperature. The first process can be produced either by supplying heat directly or, by the mechanical compression of the emanating water vapour to reach a higher pressure and, consequently, temperature, so that it can transfer heat by condensation to the evaporating brine. The second process can be produced by condensing the vapour through the use of a coolant and using a lower temperature in an evacuated vessel. This process, for example, can be obtained by evaporating water from the ocean's surface in evacuated vessels, with the condensers being cooled by colder sea water from the sea's depths, as envisaged in the ocean thermal energy conversion concept. Physically, the process is defined as the production of 1 kg of distilled water at 100^{o} C, when pressure is 1 bar, which needs 2,260 kJ of energy. If it is possible to recover all of the condensation energy, then the equation

Table 4. Standards for drinking water

Maximum	Mean	Material or characteristics
750 mg/l	250 mg/l	Suspended sediment
25 mg/l	5 mg/l	Turbidity
-	Tasteless	Taste
-	Colourless	Colour
1 mg/l	Less than 0.5 mg/l	Br (bromium)
1 mg/l	0.3 mg/l	Fe (iron)
0.5 mg/l	0.1 mg/l	Mn (manganese)
15 mg/l	1 mg/l	Cu (copper)
200 mg/l	75 mg/l	Ca (calcium)
200 mg/l	50 mg/l	Mg (magnesium)
400 mg/l	200 mg/l	SO_4 (sulphate)
650 mg/l	200 mg/l	Cl (chlorine)
Not less than 6.5, not more than 9.2	8.5-7.6	Ph (acidity or alkalinity measure) a/
4 mg/l	3 mg/l	BOD (biochemical oxygen demand)
0.05mg/l	-	As (arsenic)
0.01mg/l	-	Cd (cadmium)
0.05mg/l	-	CN
0.10mg/l	-	Pb (lead)
0.001mg/l	-	Hg (mercury)
0.01mg/l	-	Se

Source: World Health Organization, International Standards for Drinking Water (Geneva, 1963-1971).

a/ Ph is the logarithm of the reciprocal of the hydrogen ion concentration.

$E_T = E_C + E_W$ is valid, where E_W is the heat of the solution, the fundamental physical-chemical energy required to separate water from a solution (brackish or sea water). E_W is in the order of 2.1 to 2.9 kJ/kg of pure water, depending on the solution concentration (TDS). All distillation technologies try to reduce the specific input of energy to a minimum. One of the indices used to specify the steam economy of a plant is the gained output ration (GOR), which is the mass of distillate produced divided by the mass of heating steam delivered to the system. Because GOR is dependent on external steam conditions, the performance ratio (PR), i.e. the number of kilogrammes of produced water (kJ) that is put into the system is preferred (3).

Distillation processes include:

- The flash process, especially MSF;
- Multiple-effect process; with vertical or horizontal tubes;
- Vapour compression.

Table 5. Standards for irrigation water

Water class	Electrical conductivity EC X 10^6	Salt content total pmm	Sodium percentage of total salt	Boron ppm
1	0-1,000	0- 700	60	0.0-0.5
2	1,000-3,000	700-2,000	60-75	0.5-2.0
3	over 3,000	over 2,000	75	over 2.0

Source: Israelson and Hansen, Irrigation Principles and Practices (New York, John Wiley, 1962), p. 226.

Note: Class 1 is considered excellent to good, suitable for most plants under most conditions.

Class 2 waters are mentioned as good to injurious for more sensitive plants.

Class 3 is considered by the laboratory to be unsatisfactory for most crops, and unsuitable under most conditions.

(a) Flash Process

The first significant plant based on the flash process to be built in the region was in Kuwait in 1957; it had a capacity of 2,800 m^3/d and four stages. In 1985, multi-stage flash plants accounted for 90 per cent of the world's installed distillation capacity. They continue to be widely used as part of dual-purpose systems that produce both water and electricity. A giant plant with a total capacity 1,100,000 m^3/d was completed in Saudi Arabia in 1982. Multi-stage flash distillation plants have proved to be highly reliable and economic for sea water desalination, though research is continuing to improve on plant construction materials.

In the flash process, the saline water that is to be distilled is pumped through a pipe bundle in an evaporator, heated outside, and pumped in again at the bottom of the evaporator, which has a temperature of T and where the heated water temperature is equal to T + DT. As a result, heated water flashes and is partially vaporized. The vapour condenses on the pipe bundle to give desalted water (3).

Flash distillation plants that use this method to produce vapour are designed so that the incoming feed water is heated through its entire temperature range under pressure conditions that do not permit the formation of vapour during the heating process. After the maximum required temperature has been reached, the pressure on the liquid is reduced in successive stages. At each step in the reduction of pressure, there is an accompanying formation of vapour by flashing. The condensation of all these increments of water constitutes the water output of the plant.

In fact, if the flashing is realized in two stages, instead of one, and if the extreme temperature can be assumed to remain the same, total production will remain the same, but each stage will have a condensation area equal to less than half of the previous one. This is because the temperature in the first stage is higher than in the second stage. If the condensation area is maintained, reheating would be higher and the outside steam consumption lower. As a result, the PR would be higher.

In principle, the mechanism of flash vaporization, vapour purification and the subsequent condensation of the pure water product are the same. The difference is that in the multi-effect multi-stage type, there is a brine recirculation system that is divided into a heat rejection section and a heat recovery section. After passing through the heat rejection section of the distiller as cooling water, part of the saline water flows into the final stage flash chamber as make-up water, and the remainder is drained out of the system. Most of the brine in the final stage flash chamber recirculates through the distillers of the heat recovery section, one at a time, as cooling water; the small quantity remaining is drained out of the system. After recirculating through the distillers, the brine is heated to a fixed temperature in the feed water heater and fed into the initial stage flash chambers of each stage as the feed water flows towards the final stage. After being mixed with the supplementary feed water in the final stage, it is sucked in by the brine circulating pump (2), (3).

The main feature of the flash-type desalination plant is that flash evaporation keeps the plant scale-free, for longer. Continuous operation is possible without reduction in the water-producing capacity. With the flash-type plant it is possible to produce fresh water that is equivalent to 50-80 per cent of the volume of sea water feed. The multi-effect multi-stage type requires a supply of water two to three times greater than the amount of fresh water to be produced. The flash-type requires about half the total energy required by the multi-effect multi-stage type to produce the same volume of water. Multi-stage flash-type plants are suitable for handling large production volumes. Units of up to seven million gallons per day have been designed and constructed in Kuwait. Another plant in Saudi Arabia has 10 units with a total capacity of 50 million gallons per day. In such large plants, it is possible to couple the system with an extraction-type steam turbine to recover some of the power.

(b) <u>Multi-effect type plant</u>

Approximately 8 per cent of the world's distillation capacity is accounted for by this type of plant. It is efficient and installed as a dual-purpose (water and electricity) plant.

Plants such as this operate on a multi-effect evaporation concept and consist of a multi-effect section and a heat rejection section. The vapour is produced either by pressure reduction (flashing), or by heat input (boiling). Unlike the MSF process, ME operates on a once-through system with limited brine recirculation. Pump sizes are therefore smaller. As with MSF, saline water passes through the condenser tubes in the heat rejection section that is designed to be single- or multi-stage, depending on various conditions such as the temperature required for the product water and the number of effects.

Saline water passes through the condenser tubes in the heat rejection section and cools off to produce water, in addition to condensing the vapour generated from the final effect; it is then discharged from the plant. The vapour thus generated flows into the evaporating tubes of the second effect, to become the heat source of that effect. At the same time the remainder of the brine in the effect passes through nozzles, where its temperature decreases owing to partial flash evaporation; it is then sprayed over the outer surface of the second effect evaporating tubes, where a further portion of the feed is again evaporated, by being heated with the vapour generated in the first effect, which is delivered into the evaporating tubes through an eliminator section. The vapour itself condenses into fresh water, and thereby becomes the product of the plant. This cycle is repeated for each succeeding effect until the final one is completed. Vapour generated in the last effect is condensed in a heat rejection condenser. Concentrated brine is drawn out by a blow-down pump after being cooled by partial flashing in the heat rejection section.

Several plant arrangements are possible with ME. Modern plants can have vertical or horizontal tubes. The PR of the ME plant is rigidly tied to the number of effects for that plant. This condition is reversed for MSF. In order to produce a performance ratio of 10, the ME plant must have about 13 effects, while an MSF plant has between 11 and 35 effects.

(c) <u>Vapour compression units</u>

These make up 2 per cent of world distillation capacity. They are small and require a rotating energy source to operate them. Their main use is for offshore oil platforms, construction sites and sea resort hotels. They are of little importance in the ESCWA region.

2. <u>Membrane technologies</u>

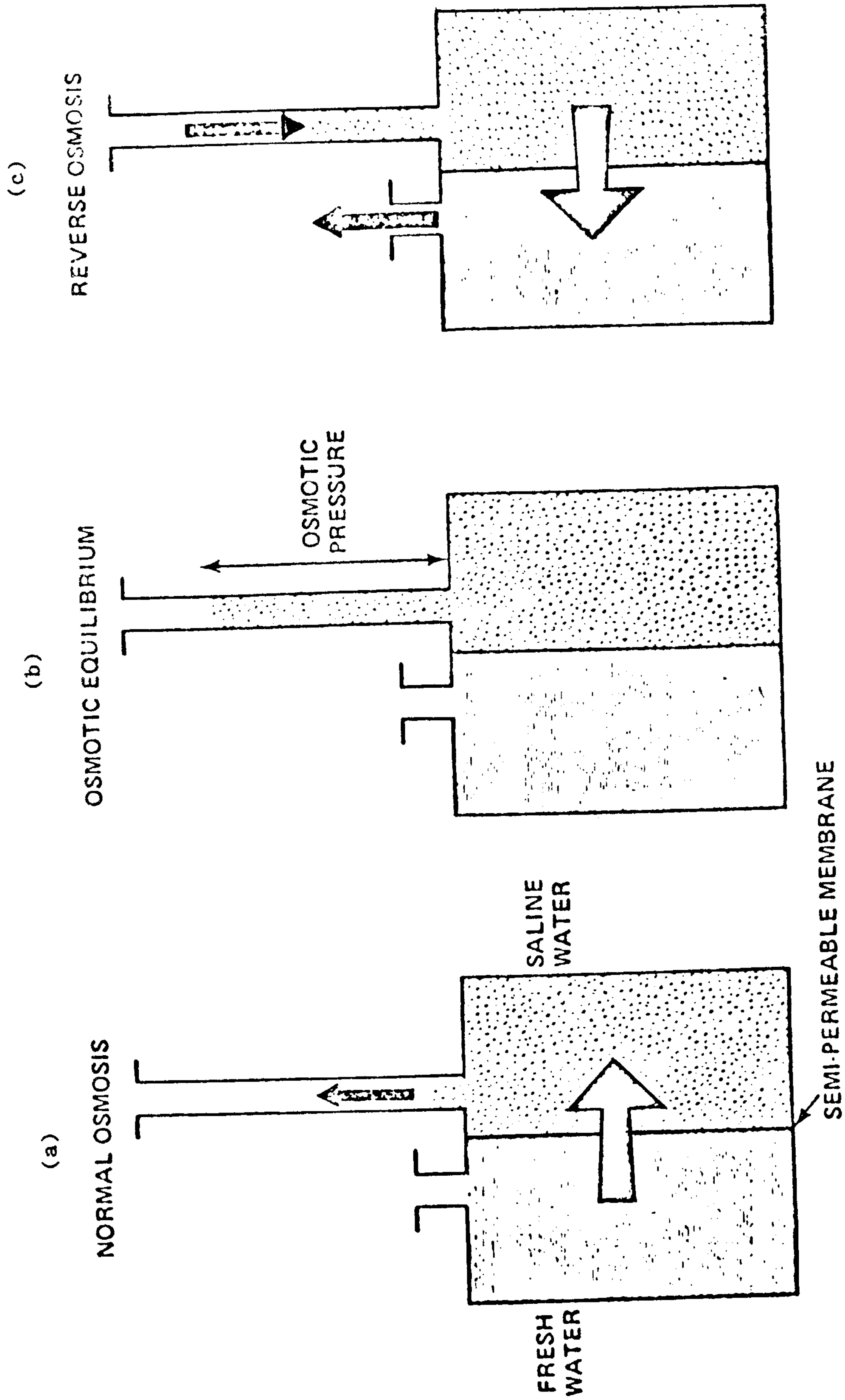
The commonest desalination processes for brackish water are ED, EDR and RO, for both technical and economic reasons. However, the results of intensive research conducted over the last few years, together with evidence from field applications suggest that this technology can also be used for sea water desalination.

(a) <u>Reverse osmosis</u>

This technique is used in more than 63 countries, and has reached a total installed capacity of 1,475,000 m^3/d since it was first put into use in the 1970s. A new development in the early 1980s is its application to sea water with TDS of up to 50,000 ppm. Reverse osmosis takes its name from the fact that water is made to pass from a more concentrated to a less concentrated solution, and this constitutes the reverse osmosis phenomenon.

Reverse osmosis can be viewed as a filtering process at the molecular-ionic level. A semi-permeable membrane is used, i.e. the membrane allows the passage of the solvent in either direction, but prevents the passage of the solution. Figure 3(a) shows normal osmosis, the natural process by which water flows through such a membrane from pure water, or from a diluted to a more concentrated solution. Every solution has a specific osmotic pressure, determined by the identities and concentrations of the

Figure 3. Principle of reverse osmosis



dissolved materials. As is shown in figure 3(b) this flow countinues until the resulting osmotic head equals the pressure of the solution. At this point, osmotic equilibrium exists, and the net flow of the water across the membrane is zero. If the solution compartment is then enclosed, and a pressure higher than the natural osmotic pressure of the solution is applied, the direction of water flow is reversed, as is indicated in figure 3(c). The solution becomes more concentrated, and purified water is obtained on the other side of the membrane.

Osmotic pressure II can be defined by the relation:

$$\Pi = CRT \qquad \text{(i)}$$

Where C is the concentration ratio of the solution, which is the molar concentration multiplied by the dissociation ratio at equilibrium, R is a constant for perfect gases, and T is the temperature in ^{o}k.

For sodium chloride (NaCl), II theoritically increases by 0.7 bar per 1 g/l salinity.

From the relationships given below, it is obvious that an osmosis plant working at high pressure will give water with lower total dissolved solids than one working at low pressure as the passage of salt is constant, as in relationship (i), and the passage of water is dependent on pressure, as in relationship (ii). The influence of temperature on Q and Q' is about the same, so that temperature modification does not affect the quantity of water produced. The passage of salts C, i.e the purity of water produced, depends on the concentration ratio and thus on the rejection ratio.

For water, the following relationship is valid:

$$Q = K \times \frac{S}{e} (\Delta P - \Delta \Pi) \qquad \text{(ii)}$$

where Q is the water flow through the membrane (m^3/time), K is the permeability coefficient of the membrane, S is the active area of the membrane, e is its thickness, P is the differential pressure between raw and treated water, and II is the differential osmotic pressure between these latter two.

For solution, the following relationship is also valid:

$$Q'(\text{salt in kg/m}^3) = K'S/e \quad C \qquad \text{(iii)}$$

where K' is the permeability coefficient of the membrane for salts, and C is the differential concentration between raw and treated water, therefore Q' is independent from P and II.

The temperature of the feed water influences the viscosity of the liquid that permeates through the membrane, which affects the maximum allowable pressure. The permeation rate increases with an increase in temperature. However, if the feed temperature is too high, this has an adverse effect on membrane stability. The maximum allowable feed temperature for a commercial membrane is 35° C. It is worth noting that the maximum allowable pressure decreases as the temperature increases, hence the effective driving pressure for permeation is reduced at high feed water temperatures (2), as can be seen from the following:

Mean pressure for ±25° C	Low	Mean	High
bar	12-14	26-28	50-70
TDS (ppm)	2,000	6,000	40,000-56,000

RO-type desalination systems can be either single or double stage. Brackish or sea water can be converted into fresh water that contains less than 500 ppm TDS in a single stage. In large reverse osmosis plants, a possibility of coupling a turbine to the system exists, and up to 40 per cent of the reverse osmosis pump energy can be recovered. In such a system, the reject brine water, which has only pressure slightly lower than the feed water can pass through a turbine and generate energy before it drops to a low pressure.

The reverse osmosis desalination system appears to have considerable advantages over systems that use distillation processes. These advantages are:

(i) The reverse osmosis system can operate at room temperatures;

(ii) It requires only mechanical power for pumping;

(iii) It results in energy savings of over 70 per cent compared with distillation processes;

(iv) RO-type plants require 30 to 80 watt/hours in order to produce one gallon of fresh water from sea water;

(v) The use of permeators that produce drinking water from sea water in a single stage, allows a compact and simple plant design that gives the lowest combined construction and operation costs of any of the desalination processes;

(vi) The designs are of a modular type and do not require long delivery periods;

(vii) Transportation and erection on site are easy;

(viii) The sea water to fresh water convertion ratio is about 25 per cent; for brackish water, this depends on the properties of the feed water and those of the product. Rates of up to 90 per cent have been realized.

Membranes used in the reverse osmosis operation must conform to certain criteria, including:

- Water flux and required pressure;

- Resistance to compaction;

- Stability of temperature in acid and alkali feed;

- Stability of cleaning solution at elevated temperatures;

- Retention of bacteria, germs and possibility of obtaining bacteriological pure water;

- Resistance to organic materials;

- Physical, chemical and mechanical durability for improved reliability (lifetime);

(h) Compatible maximum fouling index.

There are four main types of membrane: tubular (figure 4), hollow fine fibre (figure 5), flat plate, and rolled flat sheet or spiral-wound (figure 8). The hollow fine fibre and spiral-wound types are commercially the most commonly found, as they have been in use for 14 years for brackish water desalination applications, and for six years for sea water. Reverse osmosis brackish water desalination plants have proved to be reliable, especially when they are properly designed, constructed and operated.

Membranes can be made of different materials, of which the most common are:

- Cellulose acetate and additives;

- Nylon (hollow fibres) that can be of two types:

  - asymmetric aromatic polyamide (TDS tolerant up to 10,000 ppm);
  - hydrazide polyamide (TDS, tolerant up to 45,000 ppm);

- Polyether/urea composite;

- Polyether/amide composite.

Water that is to be treated by the RO process must conform to specific criteria known as the limits of the operation. Feed water cannot generally be treated by RO alone, but also has to be subject to some pre-treatment, the aim of which is to bring it up to the required quality. In certain cases, when the quality of the water produced needs to be improved further, it may be necessary to follow reverse osmosis treatment with post-treatment that is suitable for refining the quality of the final water product. Pre-treatment is essential because most of the membranes are sensitive to suspended matter, and the water must be filtered before it can pass through them; some membranes are also sensitive to chlorine (Cl_2), necessitating dechlorination by passing through active carbon. Accordingly, pre-treatment consists of active carbon to eliminate chlorine; 5 um cartidge screening in order to eliminate suspended sediments (SS) and colloids; treatment to protect membranes from alkaline earth precipitation either by acid injection or softening.

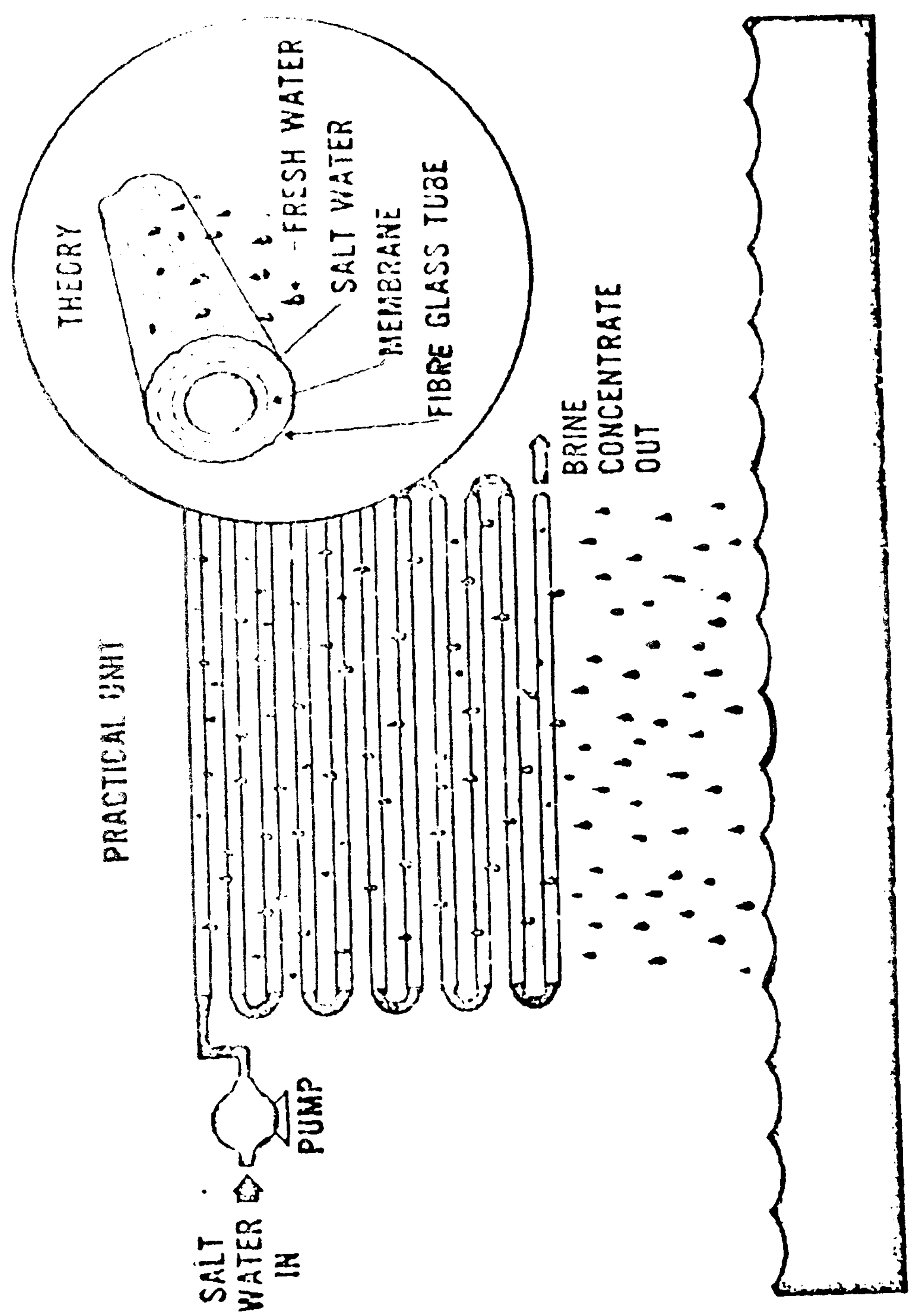

THEORY
FRESH WATER
SALT WATER
MEMBRANE
FIBRE GLASS TUBE
BRINE
CONCENTRATE
OUT
PRACTICAL UNIT
SALT
WATER
IN
PUMP

Figure 5. Hollow fine fibre reverse osmosis

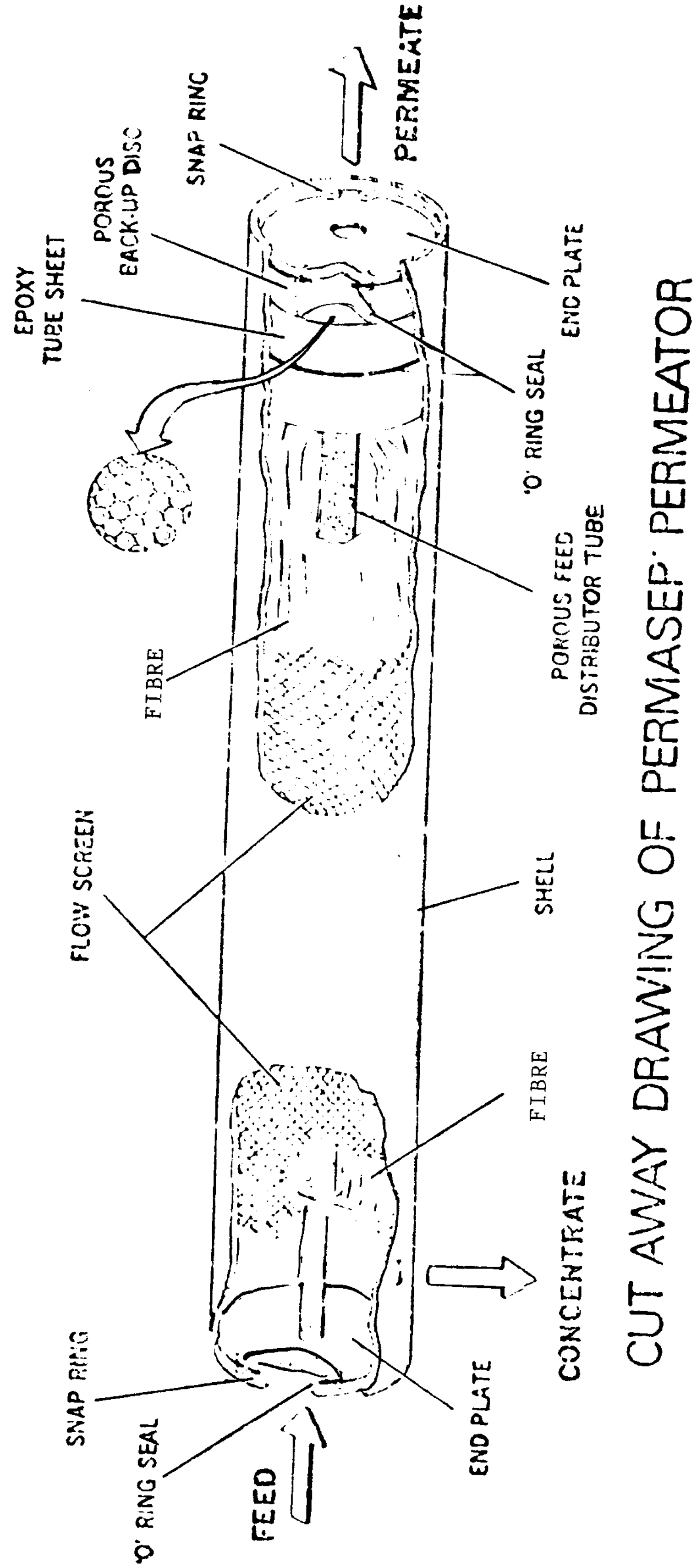
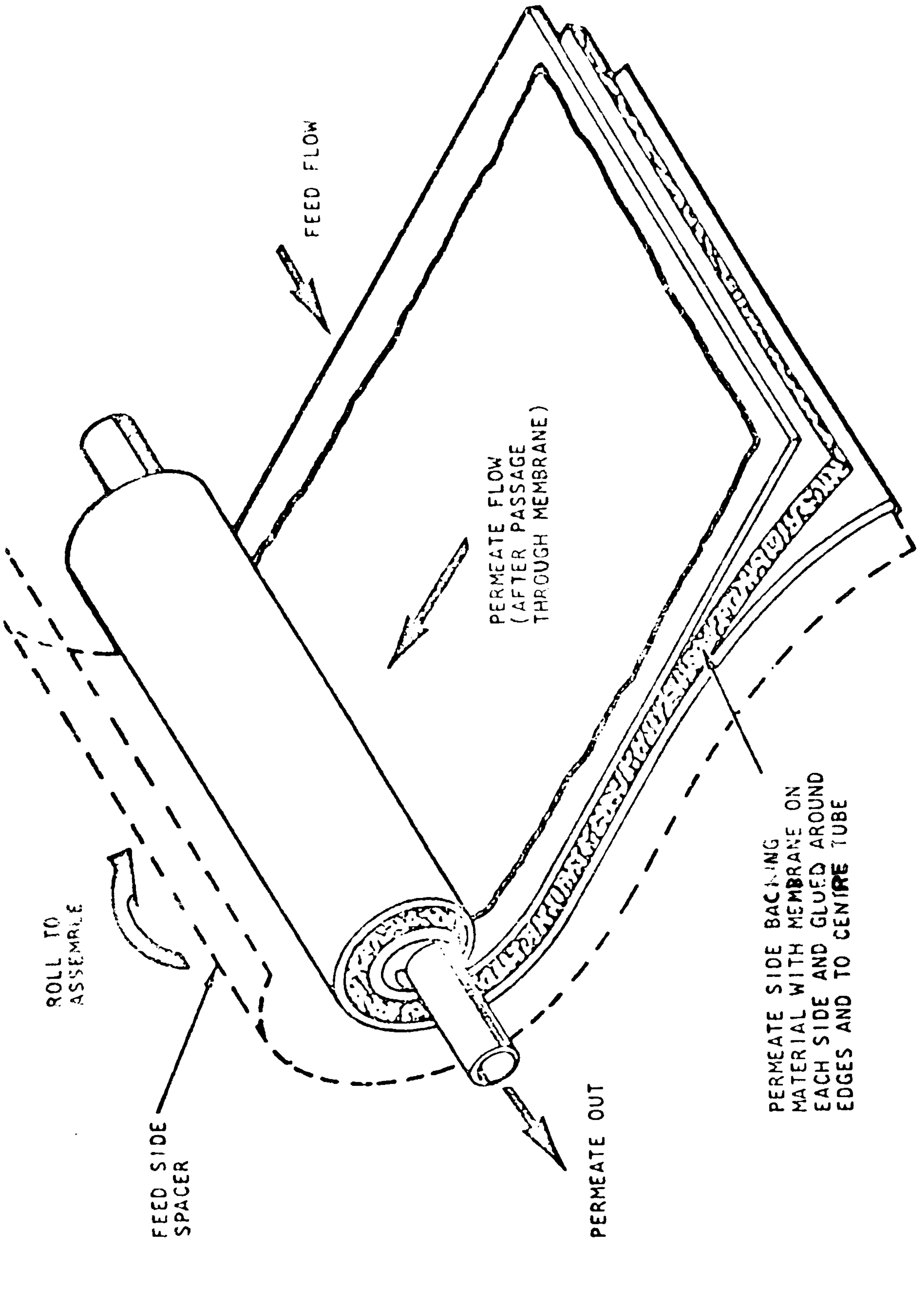


Figure 6. <u>Spiral-wound reverse osmosis</u>



(b) Electrodialysis

This process involves electrochemical separation using parts of membranes; one part selects cations and the other part selects anions. The membranes are placed alternately so as to form compartments. A direct current is placed across the resulting compartments. As saline feed water is introduced into the compartment, cations travel to the cathode and the anions travel to the anode, as is illustrated in figures 7 and 8.

The cation-permeable membrane permits positive ions, e.g. Na, to pass through, while it repels negative ions, e.g. Cl^-; the other membrane allows negative ions to pass through, but not positive ones. The membranes act as one-way check valves by preventing the re-entry of the ions they let through. Hence the space between the membrane is desalted while the streams on the electrode sides have a concentration of penetrating ions. Since the alternating membranes select either anions or cations, every other cell has a concentration of ions, while alternate compartments are depleted, which results in the production of desalinated water.

In practical ED desalination plants, multiple pairs of membranes are used between a single pair of electrodes, which form an ED stack of plastic separators that are inserted in the solution compartments so as to keep the membranes apart and to promote mixing. The cells are stacked either horizontally or vertically. The saline water flow is divided into numerous small streams, and most of the ions carried by the current are trapped in one half of the streams, and the desalted water in the other half. The required electric current varies proportionally according to the amount of dissolved solids (TDS) that are to be removed. Increasing the electrodes increases the efficiency of current utilization. The optimum number of pairs of any given design will depend upon mechanical assembly problems, sealing against water leakage and the installation and control of high voltage DC. Most designs vary between having 275 and 500 pairs of membranes for each pair of electrodes (1). The capabilities of ED, together with the other processes are summarized in tables 6 and 7.

(c) Electrodialysis reversal

By 1974, all ionic ED units were designed to use the electrodialysis reversal (EDR) principle. In the 1950s and 1960s a significant improvement was realized in the electrodialysis process following the development of electrodialysis reversal (EDR). By EDR, the membranes periodically clean themselves several times per hour through the reversal of the direct current that goes across the membrane arrays. This is the only desalination process to have this self-cleaning feature, which prevents scaling without the use of chemicals. By the EDR process, a standard ED array of alternating cation and anion membranes is separated by alternating product and brine compartments. The array is operated in the standard ED manner for a fixed period of time, and the process is reversed by an automatic timing circuit. High capacity electrodialyzers can be classified into the sheet-flow type or tortuous path type. Sheet-flow types use relatively low linear velocity, which results in a low pressure drop. Tortuous path electrodialyzers are meant to compensate for the disadvantages of the sheet-flow type. Even with the tortuous path type, it is not always possible to attain a satisfactory desalination ratio using a single stage. Consequently, two or three electrodialyzers in multi-stage are usually employed. Pressure losses are also large because of the utilization of high linear velocities.

In conclusion, desalination processes have certain characteristics that, in varying degrees, make each of them especially suitable for the desalination of brackish, as well as sea water. The capabilities and a comparison of the different processes are illustrated in tables 6 and 7. They are able to form the solutes into high concentrations in a correspondingly small volume of water. Also, they have separation factors (the ratio of feed to product water concentration). Since these characteristics, as well as cost factors, vary among the processes, all must be considered in the selection of a given application (brackish and sea water). In some cases, processes can be used more efficiently in unison where two processes are required, as each one can be used where it is more effective.

Table 6. Different desalination process capabilities

Process	Pre-treatment	Maximum brine concentration (percentage)	Process capabilities: Limits	Product quality (mg/l): Electrolyte	Product quality (mg/l): Organic	Energy consumption: Low TDS (1 Pb water/1,000 gal product)	Energy consumption: High TDS (1 Pb water/1,000 gal product)	Energy consumption: Equivalent primary fuel	Relative capital cost (0-10)
Distillation									
Multi-stage	De-aeration	25	-No Cl_2 or SS	5	Varies	12	12	85/85	10
Multi-effect	De-aeration	25	-$CaSo_4$ and	5	Varies	5	5	200/200	9
Vapour Compression	De-aeration	25	$CaCo_3$ scaling	5	Varies	50	90	60/105	10
Freezing									
Waste heat	De-aeration	25		100	99.5	10	10	15/15	10
Conventional	De-aeration	(Unverified)	Crystalization	100	99.5	45	60	55/70	10
Electrodialysis	Filter, 5 Lime soften or clarify Precipitation inhibitor pH control	15	No SS	Varies	0^o/1 1 separation	10	50	15/60	4-7
Electrodialysis reversal	Same as electro-dialysis	15	No SS	97	Varies	-	50	-/60	8
Reverse osmosis	Same as electro-dialysis	2 (brackish) 6 (sea water)	$CaSo_4$ $CaCo_3$ scaling	95 99	Varies Varies	10	40	15/45	4-7

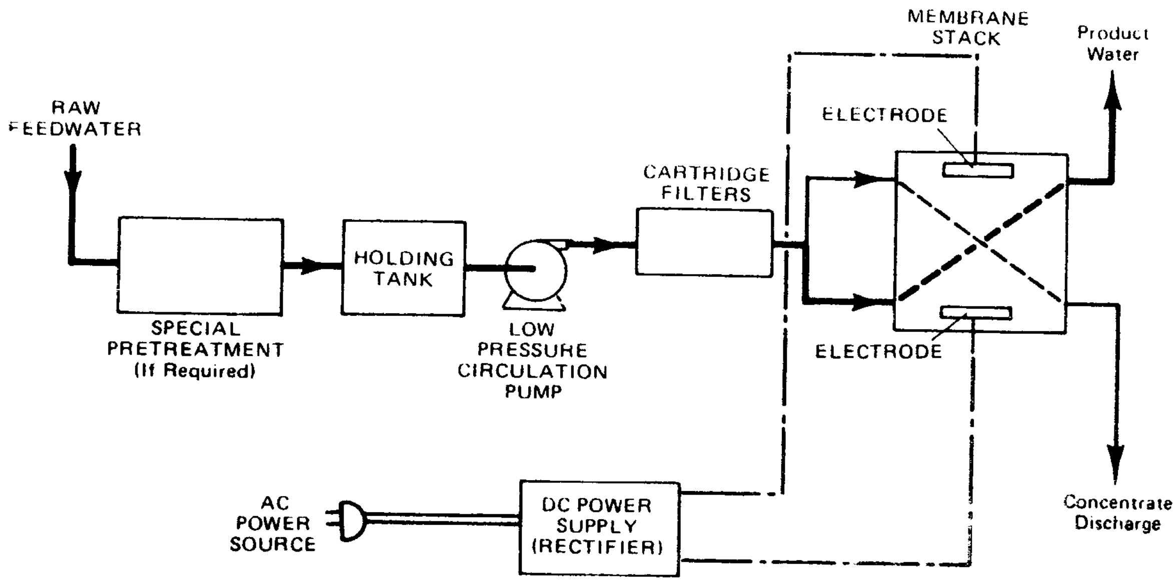
Source: United Nations, The Use of Non-Conventional Water Resouces in Developing Countries, Natural Resources No. 14 (New York, 1985) (United Nations publication, Sales No. E.84. II. A. 14), B.H. Khashaim and J.S. Williamson, eds., Solar Water Desalination; Proceedings of the Second SOLERAS Workshop, March 1981, Denver, Colorado, USA; Proceedings of the Symposium on Water Resources in Saudi Arabia, Management, Treatment and Utilization, vol. 3, Desalination, 17-20 April, 1983, King Saud University, College of Engineering.

Table 7. Comparison of desalination technologies

Process	Commercial availability	Efficiency	Capital costs	Flexibility of operation	Reliability and availability	Environmental acceptance
Distillation						
Multi-stage flash	Yes	Medium	High	None	Medium	Medium
Multi-effect multi-stage	Yes	Medium	High	Low	Medium	Medium
Vapour compression	Yes	Low	Medium	Low	Low	Medium
Freezing	No	High	Medium	None	Low	Low/Medium
Membrance						
Reverse osmosis	Yes	Medium/high	Medium	Low/medium	Medium	High
Electrodialysis	Yes	Medium	Medium	Very high	High	High

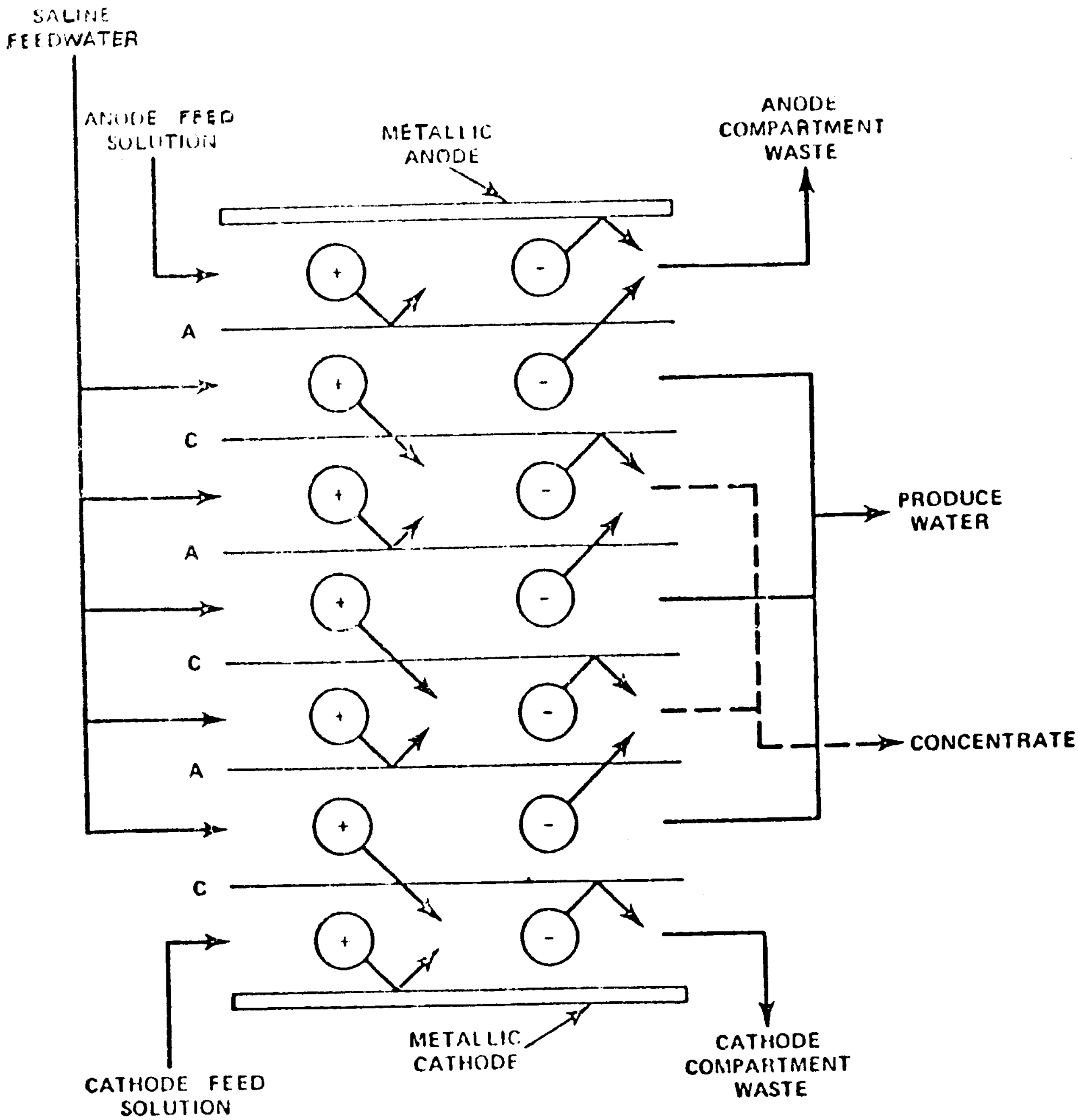
Source: Data complied by ESCWA.

Figure 7. Basic components of an electrodialysis unit



Source: Courtesy of the United States Agency for International Development, from O. K. Buros and others, USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

Figure 8. Electrodialysis stack schematic



Legend:
- A Membrane permeable to negative ions only;
- C Membrane permeable to positive ions only;
- \+ Any positive ion such as Na^+;
- \- Any negative ion such as Cl^-.

II. BRACKISH WATER POTENTIAL IN THE ESCWA REGION

A. Background

Desalination processes for the treatment of brackish water have been used for more than 30 years in different developed countries, especially the United States. As a result, hundreds of brackish water desalination plants now exist throughout the world, particularly in the ESCWA region. Desalination processes have been developed to the point where brackish water desalination technology is now considered a state of the art.

The availability of conventional water resources in the region is limited, esepcially in the Gulf countries where permanent streams are rare and rain comes in quick showers. The shortage of water has hindered the expansion of agriculture and is an obstacle to industrial development. As in other parts of the world, the availability of reasonable quantities of fresh water is crucial to the development of the Gulf countries; they could be constrained by acute water shortages, the possible exhaustion of water resources, or increases in the salinity of the water, as in many cases water is brackish or becoming brackish.

In order to develop brackish water resources, comprehensive planning is extremely important. Careful planning to guide the project from the design stage to final treatment and distribution will minimize problems. An assessment of surface and ground-water resources, the available energy in the area, the system of water distribution and the quality of water required, are all essential to the start of a project. The water quality needed to meet local requirements should be considered carefully, since in many ESCWA countries, these requirements remain below World Health Organization (WHO) standards. To this end, potential alternative water supplies should be sought, assessed and considered in the primary stages of planning. In order to make a proper assessment, hydrology and water quality in the area under study must be known. Both the quantity and quality of surface and ground water vary in the ESCWA region. Responses to a questionnaire sent to different potential sites within ESCWA countries (especially the Gulf countries) concerning brackish water desalination plants sponsored by governments, revealed a wide spectrum of water problems. Potential solutions to these water supply and quality problems are sometimes quite site-specific. Although brackish water desalination could offer a solution for many locations, it may not be economically feasible in all cases. The water quality variations that exist in the ESCWA region are shown in table 7. The water salinity levels evaluated in the study ranged from under 2,000 to several thousand ppm. Brackish water sites examined in the region vary from coastal to inland areas and include both rural and urban sites. Furthermore, certain areas suffer from specific problems such as changes in salinity caused by excessive pumping, or sea water intrusion in coastal areas. Because of the variety of actual and potential problems, good water quality data that include a complete analysis of major water constituents must be obtained. In addition, certain ions that affect desalination should be examined as they could require special pre-treatment.

Table 8. Indicative water quality analysis in selected locations within the ESCWA region

Country and location	TDS (ppm)	pH	Chemical analysis Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4
Bahrain										
Sanad	3,450	7.79	239	92.0	734	108.0	0	281	1,314	636
Wazendam	8,384	7.12	646	207.0	2,001	156.0	0	260	3,816	421
Al Markh	2,221	7.33	214	53.0	607	54.0	0	183	905	685
Bedouin Experimental Agricultural Station	2,746	7.07	246	77.0	498	125.0	0	183	905	751
Kuwait										
Abdali	4,560	7.80	170	30.0	1,262	12.0	0	146	727	2,078
Wafra	5,300	7.30	600	122.0	1,196	31.0	0	122	2,074	1,441
Shagayah	2,800	7.50	296	141.0	306	6.0	0	171	461	1,195
Solebyia	4,560	7.60	464	190.0	626	16.0	0	171	1,143	1,498
Jordan										
North-eastern desert	2,000-3,000	-								..
Azraq	5,000	-								..
Wadi Araba	2,000-2,500	-								..
Qatar	2,000-2,500	-								..
Oman										
Hafit East	4,112	-	545	166.0	405	14.5	0	0	227	1,575
Hafit West	4,697	-								..
Masah	3,386	-	224	27.7	310	15.4	-	-	325	1,130
Saudi Arabia										
Al Qatif	2,452	-	215	539.0	531	34.0	-	169	1,046	418
Al Hufuf	2,500-10,000	-								..
Al Qasim	2,000-10,000	-								..
Al Quwaiyah	2,000- 7,000	-								..

Source: ESCWA, based on responses to questionnaire.

In addition to the above, differences in riparian rights make it inherently difficult to find regional solutions to water problems. Desalination processes that are particularly adaptable to potable water production at specific locations could help to solve these problems. One of the particular advantages of membrane desalination processes is that the plant can be constructed in a relatively short period of time. Generally speaking, sea water desalination plants are more difficult to design and construct than brackish water plants, and it is reasonable to say that they can be constructed in a shorter period.

The selection of a brackish water desalination process depends on several factors, including:

- Brackish water available in reasonable quantities;
- Salinity (total dissolved solids);
- Required product water quality;
- Brine disposal facilities;
- Pre-treatment requirements;
- Availability of energy;
- Economic feasibility.

Hence, the proven technology for brackish water desalination is the membrane process that includes ED, EDR and RO.

A questionnaire was sent in the course of 1986 to member countries (see annex 1) to identify and enquire about the following:

- Brackish water locations in the ESCWA region;
- The quantity of available brackish waters, their location and uses;
- The quality and predominant dissolved solids;
- Current desalination plants in operation: their location and cost.

Before describing the water resource development situation in selected member countries, it might be useful to briefly consider the regional hydrogeological conditions that prevail in the ESCWA region.

B. Regional hydrogeological conditions

In order to assess the role that brackish water desalination processes can play in supplementing water resources in the ESCWA region, it is first necessary to define the location, quantity and quality of available brackish ground-water supplies. In addition, it is important to know the rate of recharge of the underground aquifers, and if appreciable ground-water withdrawal can be undertaken. In general, the brackish water that exists in the ESCWA region is always thought of as an asset and used in agriculture, while in some countries it is blended with fresh water in an effort to diminish its salinity and to avoid any adverse effects on plants. There is still a paucity of data on ESCWA brackish ground-water resources. The available information can generally be traced to hydrogeological prospecting for fresh water resources or for oil. In the Arabian peninsula there are many aquifers with a water age of about 25,000 years. The water is contained in closed hydrological basins with a potential for recharge. The aquifer formations are composed of Nubian sandstone and limestone series from the Cretaceous Jurrasic age, along with river beds and surface formations of a more recent age (Quaternary). Brackish water also exists in coastal plains and is sometimes mixed with sea water resulting from sea water intrusion.

Based on hydrogeological conditions, the region can be subdivided into two main categeories (see map 2):

1. The Arabian peninsula block, which contains Saudi Arabia, the Gulf countries and the two Yemens;

2. The Arabian platform, which is made up of Iraq, the Syrian Arab Republic, Jordan, Lebanon, Gaza and the West Bank (4).

1. <u>The Arabian peninsula block</u>

The Arabian peninsula block includes major geological structures that have a direct effect on existing hydrogeological conditions.

The geological structures encompass:

(a) The Arabian shield, which contains the great Najd area and the wide plateau towards Yemen that comprises:

(i) The Western Arabian shield that forms the central Najd-Hijaz and Asir highlands;

(ii) The Yemen Plateau that extends to Aden;

(iii) The Southern Arabian shield along the Arabian sea coast.

These receive a relatively high annual rainfall of up to 500 mm/year and provide active recharging zones for existing aquifers. The aquifers are:

- The intra-mountain plains;
- Flood plains;
- Sedimentary sequences between the basement complex and Tehama;
- The Arabian sea and Batinah coastal plains.

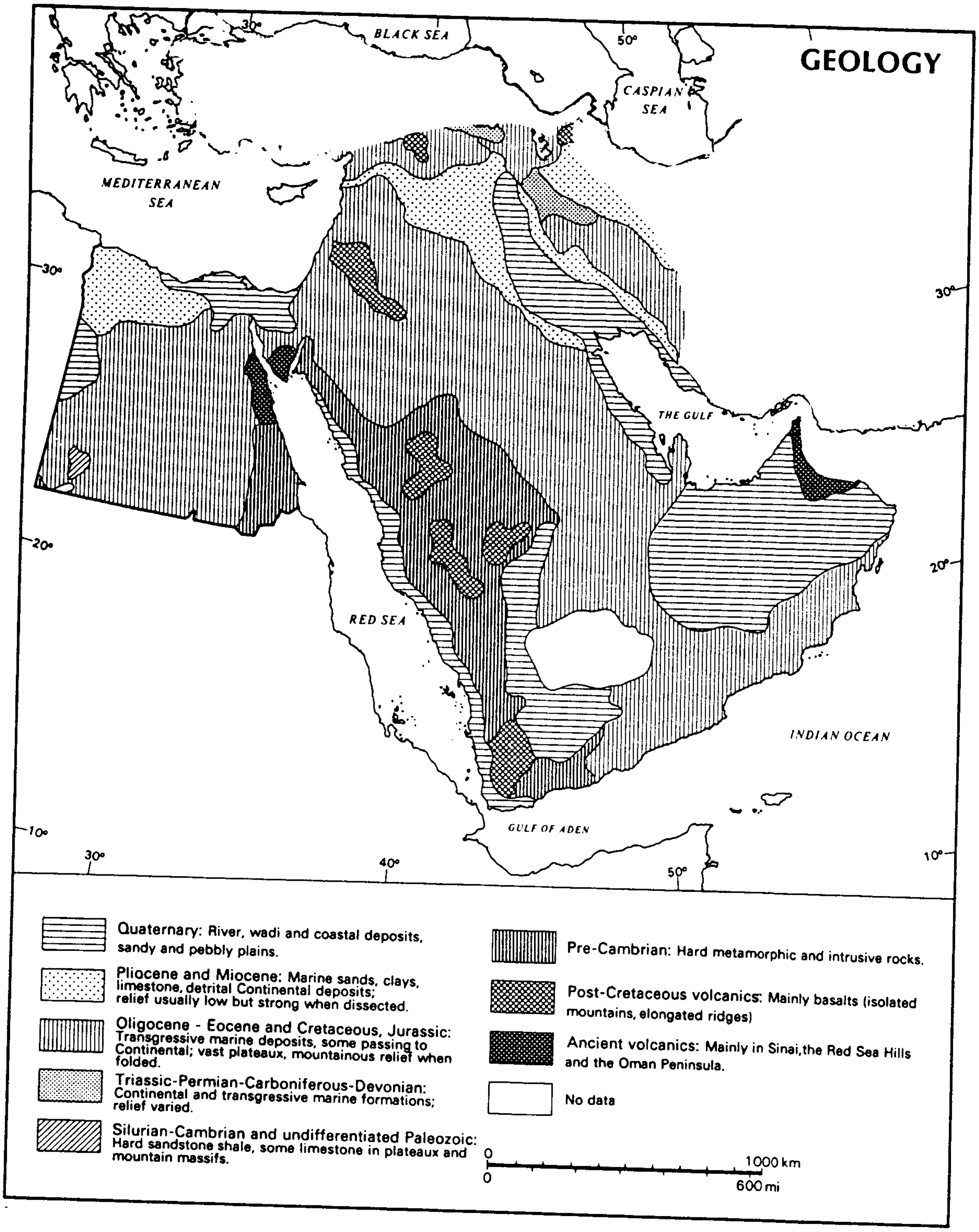
(b) <u>The Arabian shelf</u>

Essentially, the Arabian shelf is made up of sedimentary sequences that contain all the aquifers in the Arabian peninsula block. The Arabian shelf consists of:

(i) The interior homocline that resulted in a wide synclinarium in the north in Wadi Sirhan (Saudi Arabia and Jordan, a broad anticline near Hail (Saudi Arabia), and a gentle syncline in the Rub-el-Khali;

(ii) The interior platform caused by the block-type movement along the Arabian Gulf;

Map 2. General geology of Western Asia and Egypt



Source: Based on map 5 of Ground Water in the Eastern Mediterranean and Western Asia, the Department of Technical Co-operation for Development (United Nations publication, Sales No. E.82.II.A.8).

(iii) The basins that include Rub-el-Khali, the northern Arabian Gulf, and the north-east of Saudi Arabia.

In this block, the main aquifers in the subregion belong to Palaeozoic sands, Mesozoic sands and carbonates rocks, Tertiary carbonate rocks and Quaternary alluvium. Ground water quality deteriorates generally towards the inland basin and the coastal areas, where the possibility of brackish water existence is high.

Table 10 shows the regional hydrogeological sections of the ESCWA region.

2. The northern and north-eastern Arabian platform

The significant geological structure that affects water-bearing formations is the north-east secondary split of the African Rift Valley system which runs from Aqaba in Jordan to the Karasu Depression in Turkey. The structure is formed by Wadi Araba, the Jordan Valley, Lake Tiberias, Hula, Beka'a, Al-Ghab and the Massyaf Depression in the Syrian Arab Republic, Lebanon and Jordan. The other geological structure is the zone of marginal troughs, thrusts and neogene folding in eastern Iraq, the north and north-east of the Syrian Arab Republic and southern Turkey.

In the Arabian platform, ground-water resources exist in Palaeozoic sandstone, Jurassic Cretaceous-Palaeogene carbonate rock aquifers, Tertiary volcanic and Quaternary alluvium. Their quality ranges from excellent to brackish. Good quality resources occur at the foothills of the recharging areas, and deteriorate generally eastwards in the inland basins and areas of the Syrian Arab Republic and Jordan, and westwards from the Zagros mountains in Iraq (4).

C. Brackish water availability in the ESCWA region

As was mentioned before, most of the information on the brackish water available in the ESCWA region comes either from hydrogeologic prospecting for fresh water resources or oil. The purpose of this section is to consider the available information on brackish water within each country's overall water resource condition. The information was obtained from the questionnaires distributed to concerned officials in ESCWA countries, or during the missions undertaken to these countries. It shows that brackish water in the region is limited and of different quality. Table 11 gives brackish water qualities and locations horizontally and vertically, together with its current use in the different ESCWA countries.

The following is a country summary of the brackish water available, where emphasis is placed on hydrogeological conditions.

1. Bahrain

Bahrain is an archipelago of 33 islands in the Arabian Gulf, roughly mid-way between the east cost of Saudi Arabia and the west coast of the Qatar peninsula. It has a total land area of about 660 square kilometres. The main island of Bahrain acounts for 85 per cent of the country's land area, where the capital of the State, Manama, and other important centres like the port,

Table 9. Regional hydrogeology of the Arabian peninsula

Era	Period	Epoch	Saudi Arabia: Formation	Saudi Arabia: Lithology	Saudi Arabia: Aquifer charact.	Qatar and Bahrain: Formation	Qatar and Bahrain: Lithology	Qatar and Bahrain: Aquifer charact.	Oman and U A E: Formation	Oman and U A E: Lithology	Oman and U A E: Aquifer charact.	Yemen Arab Republic: Formation	Yemen Arab Republic: Lithology	Yemen Arab Republic: Aquifer charact.
CENOZOIC	Quaternary			all.					Holocene	sand,gravel congl.silt and evap.	good		Basalt alluvium	good
	TERTIARY Neogene	Pliocene & Miocene	Hofuf	l.s.,gyp. sandy marl,l.s		Fars	sandy marl and sandy l.s	fair to good						
			Dam	marl,sh.,s.			marl,sh.s.s.			marl,clay evap.		Trap series	volcanics / sand,gravel,cl. and l.s. / volcanics	fair to good
	Paleogene	Oligocene	Hadrukh	calc.slt.s.										
		Eocene	Dammam	l.s. dol.	fair	Dammam	Dol.l.s.,l.s.		Dammam	limestone	fair			
			Rus	marl,chk.l.s.		Rus	l.s.,dol,gyp	good	Rus	l.s.,massive marls,gyp.				
		Paleocene	Um er radhuma	l.s.dol.l.s.	good	Um er radhuma	Dol.,chert,marl clay		Um er radhuma		good	Majd-sir	Coarse clastics	
MESOZOIC	CRETACEOUS Upper	Meastrichtian Campanian Santonian	Aruma gp	l.s.		Aruma gp	calcarenites &		Fiqa Muti Qumayra ? basic rocks	Samail gp basic, ultra basic rocks; shales and l.s.	fair	Tawilah	quartz s.s. with red fine clastics	variable
		Taronian ? Cenomanian	Mishrif Rumaila Ahmadi Wara (Wasia Group)	sandstone with shale	good	Mishrif Khatiah	limestones & dolomites	saline water	Wasia gp.	Hawasinah gp unknown age ?; l.s.	fair			
	Lower	Albian ? ? Aptian ? ?	Mauddud Safaniya			Mauddud Nahr Umr	& sandstone & shale		?			?		
		Neocomian	Riyadh	sandstone & shale	fair	Shuaiba Hawar Khoraib			Kahmah gp.	l.s.,shale dolomite		? unnamed ?	shale, marl, carbonates,evap.	
			Buwaib	calc.l.s.										
			Yamama	Calcarenite		Yamama								
	JURASSIC Malm	Berriasian Tithonian	Sulaiy Hilth	chk.l.s. anhydrite		Sulaiy Hilth			?		good in Oman			
		Kimmeridgian	Arab	calcarenite & l.s.		Qatar Fahahil	carbonate rocks			Hajar Super Group		Amran	evaporites and related carbonates	
		Oxfordian	Jubaila Hanifa	Aphanitic l.s		Darb Diab			Sahtan gp	shale,l.s. and dol.				
	Dogger	Callovian	Twaiq											
		Bathonian	Dhruma	Aphanitic l.s and s.s.	good	Uwainat							marine carbonates	
		Bajocian												
	Lias	Toarcian	Marrat	shale and l.s.		Izhara Absent						Kholan	continental quartz s.s. with red fine clastics	fair to good
	TRIASSIC Up.		Minjur	s.s. and sh.		Gulailah								
	Mid.		Jilh	Aphanitic l.s and s.s.&sh.		Suwel	*	*	Mahil	Dolomite	fair	Absent		
	Low.		Sudair	shale		Khail Sdair								
PALEOZOIC	Permian carboniferous		Khuff Wajid Jauf	l.s.,sh ands.s. sandstone	good	Khuf Prekhuf			Saiq	Dolomite		Wajid	Clean quartz s.s.	?
	Devonian Silurian Ordivician Cambrian		Tabuk Saq	l.s.,sh. s.s. sh. s.s.	v.good									
PRECAMBRIAN				Basement Complex						Basement Complex			Basement Complex	

all. alluvium
arg. argillaceous
calc. calcareous
cl. clay
chk. chalk
cht. chert
congl. conglomerate
dol. dolomite
evap. evaporites
gyp. gypsum
l.s. limestone
sh. shale
s.s. sandstone
volc. volcanics

Table 10. Regional hydrogeology of the north/north-eastern block of the ESCWA region

ERA	PERIOD	EPOCH	SYRIA: Formation and Lithology	SYRIA: Aquifer charact.	LEBANON: Formation and Lithology	LEBANON: Aquifer charact.	JORDAN: Formation	JORDAN: Lithology	JORDAN: Aquifer charact.	IRAQ and KUWAIT: Formation	IRAQ and KUWAIT: Lithology	IRAQ and KUWAIT: Aquifer charact.
CENOZOIC	Quaternary		all., marl. congl.	poor	alluvium	fair to poor	Alluvium	soil, s., gravel		Dibdibba	sand & gravel with sandy cl. and gyp.	good
CENOZOIC	TERTIARY – Neogene	Pliocene & Miocene	clay, s.s., l.s., congl. with volc. PARS l.s., cl., marl, gyp. cl. marl, l.s., l.s. arg., s.s. and cl.	fair	l.s. and marl clastics, gyp., marl l.s. marl, l.s.		Jordan Valley	marl, cl., and evaporites conglomerate with silicious sand, gravel	poor / fair	L.Fars / Char	calc.s.&gravel quartzitic sand & gravel, silt	fair
CENOZOIC	TERTIARY – Paleogene	Oligocene	L.S. arg., s.s.		Absent							
CENOZOIC	TERTIARY – Paleogene	Eocene	l.s. arg. l.s. l.s., marl, chert marl, chalk, clay	good	l.s., chert l.s., marly l.s. chert, marl, chert l.s.	fair	Balqa	l.S, chk, marl / cht & l.s.	poor / good	Dammam / Rus / Um Er Radhuma	limestone / marl, clay / limestone	fair to good
CENOZOIC	TERTIARY – Paleogene	Paleocene		poor			Balqa	chk, marl &				
MESOZOIC	CRETACEOUS – Upper	Maestrichtian Campanian Santonian	chk, marl, marly l.s. cht. chert chk	fair	CHEKKA chk, marl l.s., phosphorous chk. l.s.. cht	fair	Balqa	marly l.s. / cht., l.s., phos. / chk, marl, marly l.s.	poor / good / poor	Tayarat / Qurnah / Hartha / Sadi	limestone / marl / limestone / limestone	
MESOZOIC	CRETACEOUS – Upper	Taronian ? ?	l.s., marly l.s.	good	GHAZIR l.s., marl	v.good	Ajlun	l.s., dol.&Cht. l.s., marly l.s. dol., dol. l.s. marl, marly l.s. l.s., dol. l.s.	good	Magwa / Ahmadi / Wara	marl and marly l.s. / marl / debris	
MESOZOIC	CRETACEOUS – Upper	Cenomanian	l.s., marl and local volc.		SANNINE l.s. l.s., dol l.s. marl and cht					Mauddud	limestone	*
MESOZOIC	CRETACEOUS – Lower	Albian	l.s. arg., l.s., marl	poor	s.s., l.s. marl and marly l.s. JEZZINE sand arg. s. l.s., l.s. s.s. and evaporites	fair to poor	Kurnub	sand shale clay and sandy limestone	poor	Burgan / Shuaiba / Zubair	debris / limestone / debris	
MESOZOIC	CRETACEOUS – Lower	Aptian ? ?	sh., l.s., s.s.& volc.									
MESOZOIC	CRETACEOUS – Lower	Neocomian	not recognized							Ratawi / Yamama / Sulaiy	marls / marly l.s.	
MESOZOIC	JURASSIC – Malm	Berriasian Tithonian	" "		Salima Volc. l.s., marl. oolitic l.s. karst. BHANNES volc and marl BIKFAYYA l.s. and dol.l.s.		Kurnub	sandstone marl and shale		Gotnia	marly l.s. sandstone quartzitic	*
MESOZOIC	JURASSIC – Malm	Kimmeridgian	limestone									
MESOZOIC	JURASSIC – Malm	Oxfordian	limestone, clay			v.good	?			Najmah	limestone	
MESOZOIC	JURASSIC – Dogger	Callovian	dolomitic l.s.	good in maritime area	KESROUANE l.s. and dol.l.s.		Zarqa	limestone, marl stone, sand-stone and shale	poor	Sargelu	marly l.s. l.s. and clay	
MESOZOIC	JURASSIC – Dogger	Bathonian	and									
MESOZOIC	JURASSIC – Lias	Bajocian Toarcian	limestone ?									
MESOZOIC	TRIASSIC – Up.		exotic blocks,				Zarqa	limestone, shale sandy limestone marl and evaporites		Alan / Mus / Adaiyah / Butmah / Baluti to Mirga Mir	marl sandy l.s. / limestone shale and sand-stone	*
MESOZOIC	TRIASSIC – Mid.		ophiolites-	poor	*	*						
MESOZOIC	TRIASSIC – Low		radiolites									
PALEOZOIC	Permian Carboniferous Devonian Silurian Ordivician Cambrian		marly limestone with spiriferous and l.s. ?	?			? / Khreim / Disi	? / s.s., slts, shale quartzite, s.s. arkose	v.good	Chia Zairi / Harur / Ora / Kaista / Pirispiki / Khabour	limestone / limestone / shale / Red beds / Quartzite, sh.	*
PRECAMBRIAN								Basement Complex			Basement Complex	

- all. alluvium
- arg. argillaceous
- calc. calcareous
- cl. clay
- chk. chalk
- cht. chert
- congl. conglomerate
- dol. dolomite
- evap. evaporites
- gyp. gypsum
- l.s. limestone
- sh. shale
- s.s. sandstone
- volc. volcanics

Source: United Nations, Economic Commission for Western Asia, Assessment of Water Resources Situation in the ECWA region. (Beirut, 1981), pp. 19 and 22. (E/ECWA/NR/L/1/Rev.1)

Note: ... Data not available.

oilfields and refinery are located. Rainfall is low, the average annual precipitation is around 75 mm. Summers are characterized by high temperatures and humidity. Winters are mild, with temperatures of around 20° C or less.

Until 1930, Bahrain depended heavily on natural surface springs to meet its need for domestic and agricultural water. These springs were located on the northern half of the main island and, to a certain extent, on other smaller islands. Surplus water in the springs used to find its way to the sea through narrow streams. Hand-dug wells were also in common use in some areas. As a result of oil exploration, demand rose greatly and this, in turn, necessitated the exploration and tapping of ground water that exists under artesian conditions. In the 1940s, improvements were made to the mode of distribution in urban areas by the introduction of a piped water supply system and the introduction of service connections to houses. As urban areas grew larger and larger, more and more boreholes were added, along with similar distribution arrangements.

Water supply in Bahrain for domestic and agricultural purposes thus traditionally depended on the ground water extracted from two fresh water aquifers: the Alat and the Khobar (see table 9). These aquifers are extensions of the geological structures that extend under eastern Saudi Arabia, where considerable quantities are also extracted from them (see figure 9). The Alat aquifer has since deteriorated and become unfit for domestic use, but it is still used for agricultural purposes in certain areas. At present the Khobar aquifer is the only water-bearing strata from which water is extracted for domestic use. There is a third aquifer below the Khobar which is known as Umm er Radhuma, whose salinity varies between 1,000 to 3,300 mg/litre, i.e. it is brackish (see figure 10).

In 1969, annual water consumption for domestic and industrial purposes in Bahrain was 19.3 Mm^3 (11.63 Mgd) which rose steadily to 44.7 and then 92.9/Mm^3 in 1980 and 1986 respectively. Together with agricultural requirements, ground-water extraction reached its maximum in 1981/1982, i.e. 160 Mm^3/year, beyond which it would start to have an adverse effect on water quality. Total dissolved solids (TDS) in water rose from an initial level of about 2,200 mg/litre to about 3,000 mg/litre by 1982 in Sitra, Hidd, Tubli, etc., which is beyond the brackish level of 5,000 mg/litre (5).

2. Democratic Yemen

Democratic Yemen is renowned for its poor water resources. Rainfall does not exceed 100 mm/yr in most parts of the country, but in the mountainous region it can reach 400 mm/yr.

Perennial wadis are absent in Democratic Yemen. Surface water (around 1,400 Mm^3/yr) occurs during the rainy season and serves to rechange aquifers, or is used in agriculture with the help of dikes. Peak floods usually flow to the desert or to the sea during rainy seasons. Ground water, mostly of brackish quality, ranges from 1,000-3,000 ppm, is generally utilized for domestic and certain agricultural uses. Traditionally, agriculture depends on seasonal rain, mostly the short, intensive summer monsoons. The construction of dams has been proposed. No desalination plants exist in Democratic Yemen (4), (5), (6).

Table 11. Brackish water availability in ESCWA countries

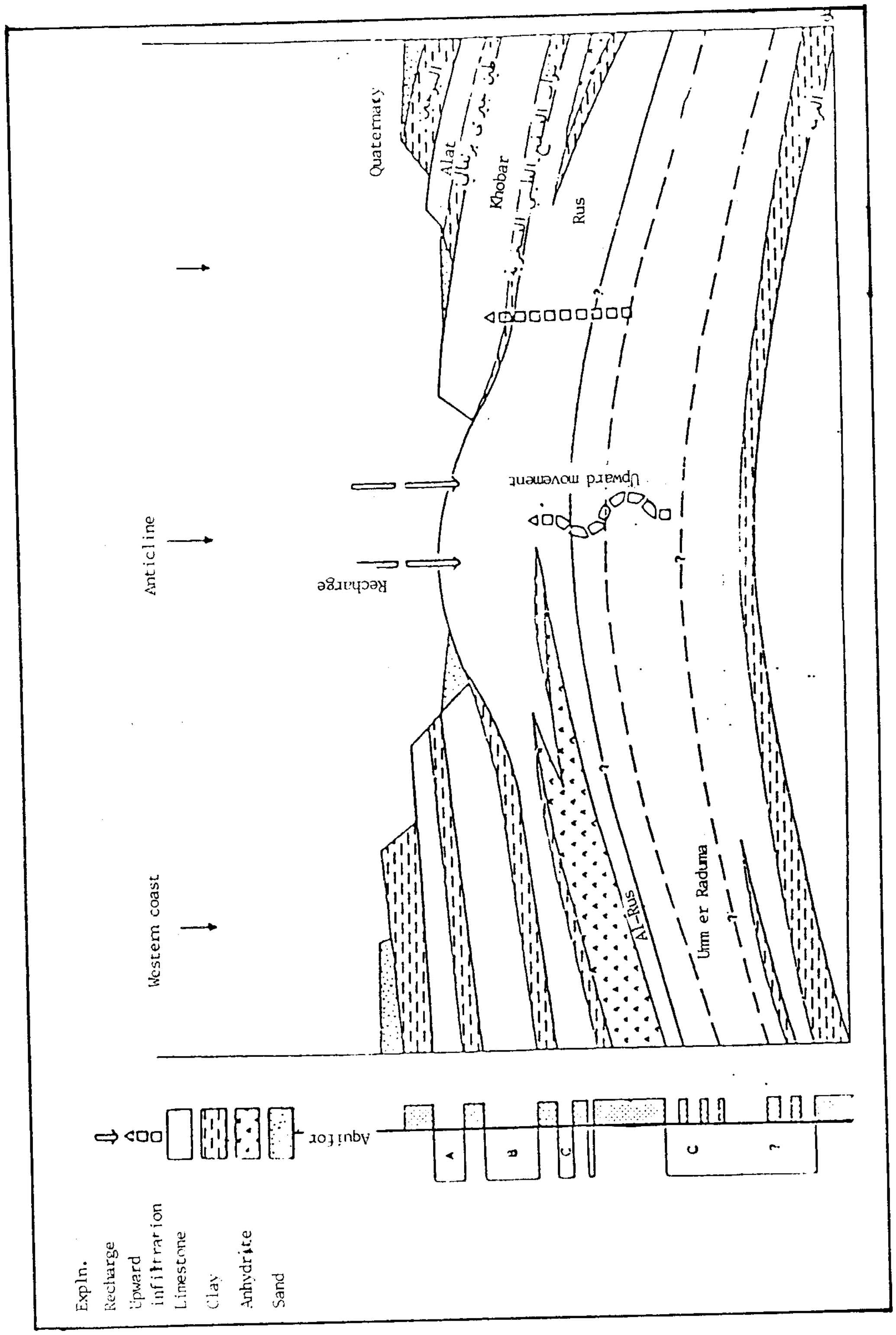
ESCWA member	Brackish water location	Aquifers	Depth of aquifer from ground (m)	Present use	Quantity
Bahrain	Main island of Bahrain	Khober (B)	30-39	Water supply, irrigation	90 million/year (100 per cent country water resources)
Democratic Yemen	Coastal areas along the Arabian Sea (sea water intrusion)	Quaternary alluvium	50-80	Water supply, irrigation	60 MCM/year (Wadi Tiban) (Data on other water basins is not available)
Egypt	Max pumping station, Parsik pumping station, lower pumping station No. 8; pumping station No. 7; Bahr el Baqar; Sinai	(Return flows) Nubian sandstone	.. 200-300	Irrigation	3.865 billion/year (3.4 per cent of country's total water resources)
Iraq	Mesopotamian plain to Tharthar, Lower Fars, alluvium Main overflow drain (MOD)	Quaternary alluvium Return flows	10-50 -	Water supply, irrigation -	Not available
Lebanon	Coastal areas (sea water intrusion)	Recent alluvium and carvernous limestone	5-10	Water supply	Not available
Jordan	Jordan Valley Azraq W. Dhuleil North-eastern/eastern desert Wadi Araba Return flow	Alluvium Belqa - B_2 Basalt Belqa 2 Alluvium -	0-100 10-50 10-60 150-200 30-70 ..	Irrigation by direct application or blended with fresh water	5 Mm^3/year
Kuwait	Soleibeyah Shagayah Wafra Abdali	Kuwait Khobar Umm er Redhuma	30-100	Irrigation Blended with desalinated sea water	Not available
Qatar	Northern province Southern province	Rus Um er Redhuma	20-80	Direct use for agriculture Blended with desalinated water, Desalination on a small scale	30 per cent of Qatar's total available water resources

Table 11. (continued)

ESCWA member	Brackish water location	Aquifers	Depth of aquifer from ground (m)	Present use	Quantity
Oman	South and east of Batinah coast covering 12,600 hectares	Batinah alluvium	up to 100	Irrigation (direct use)	15000 m^3 per hectare is extracted annually, consisting of 25 per cent of water used for irrigation
	Capital area	Tertiary limestone	up to 100	Blending with desalinated (MSF) sea water, for domestic use	3,000 m^3/d
	Dhufar	Limestone	100-200	Irrigation	
West Bank and Gaza Strip	Jordan Valley	Alluvium	up to 100	Irrigation	60 Mm^3
	Wadi Araba	Alluvium	up to 100	Irrigation	
Saudi Arabia*	Al-Qatif	Khobar	130	Irrigation	150 m^3/Hour per well
	Hufuf	Umm er-Radhuma	240-350	Irrigation	Not available
	Wadi Al-Rash/Qasim	Saq	170-325	Irrigation	Not available
	Al-Quwayah	Khuff	90-170	Irrigation	Not available
	Rus-south	Wadi Alluvium	40-70	Desalination irrigation	Not available
Syrian Arab Republic	Mesmeyah	Huran	120-200	Mainly for irrigation	Not available
	Wadi Al-Miah	Limestone	200-250		
	Khanaseer basin	Chert/limestone	200-250		
	Halab	Marl	300		
United Arab Emirates	Al-Sirrah	Alluvium		Irrigation	
	Batinah coast			Desalination	
	West coast			Blending with desalinated sea water	Not available
Yemen	Tihama	Alluvium (sea water intrusion)		Irrigation	Not available

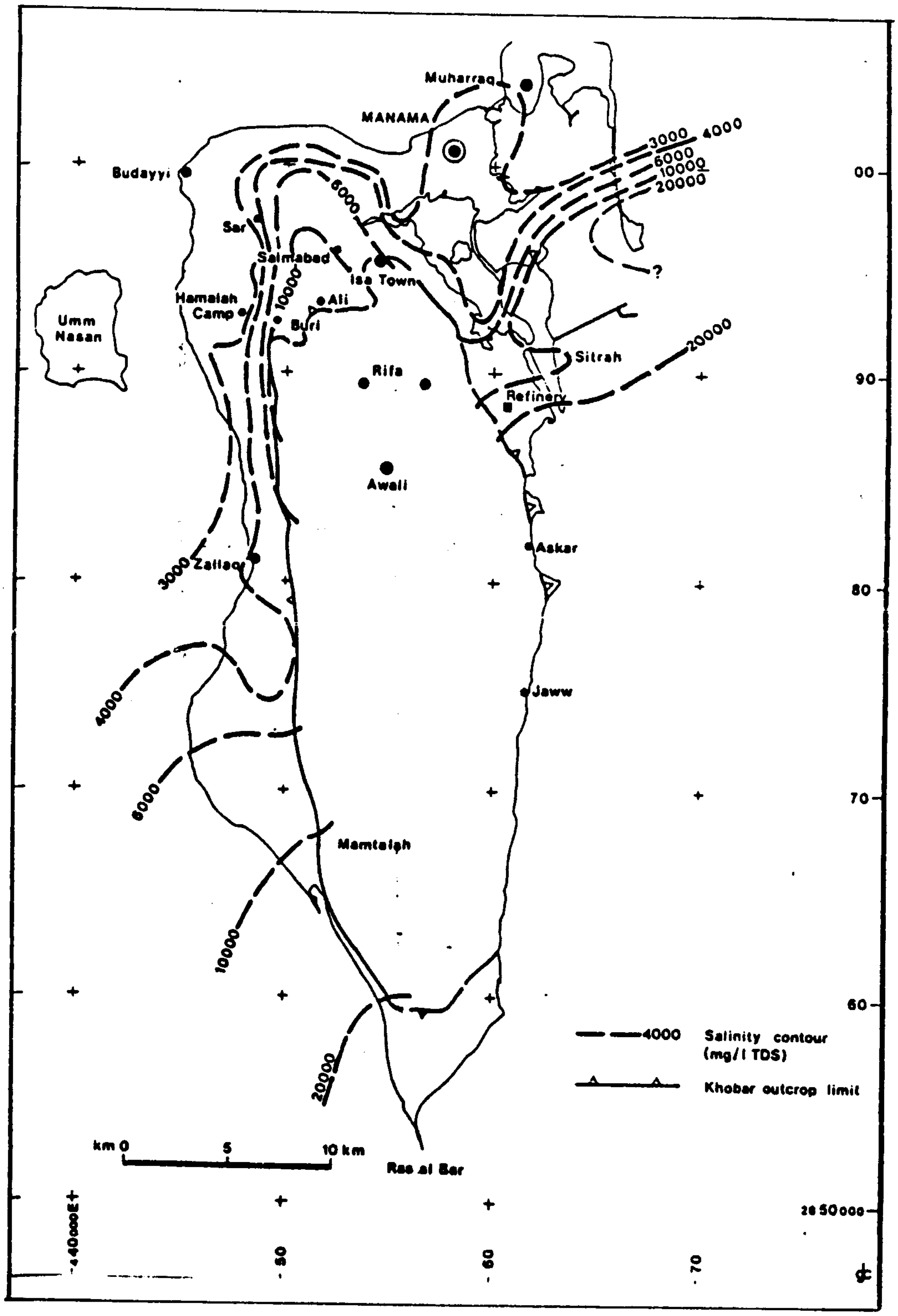
Source: ESCWA estimates, based on responses to a questionnaire sent by the ESCWA secretariat; United Nations, Department of Technical Co-operation for Development, Ground water in the Eastern Mediterranean and Western Asia, Natural Resources, Water Series No. 9 (New York) (United Nations publication, Sales No. E.82.II.A.8); United Nations, ESCWA, Food security in the West Bank and Gaza Strip (1985) (ESCWA/AGR/85/4).

Figure 9. Diagram showing aquifer systems in Bahrain



Source: Data supplied by Bahrain, Ministry of Agriculture and Fisheries.

Figure 10. Khobar aquifer salinity in Bahrain



Source: Bahrain, Ministry of Agriculture and Fisheries, 1986.

3. Egypt

Apart from the Nile, which provides Egypt with all of its water supplies for different uses, ground-water aquifers are located in basal clastics (Nubian sandstones), the sand and gravel section deposited in the Nile Delta (Pleistocene Nilotic deposits), fissured limestone aquifers, and the Mediterranean calcarenites in the coastal plain. Water quality in these aquifers is up to 1,000 ppm, which does not make them brackish. Some locations in Sinai are brackish, but the quality limits are still within human and agricultural use. Brackish water is absent in Egypt.

4. Iraq

Iraq's total area is 434,920 square kilometres. It is divided into five physiographical regions, the mountain region, the foothills, Jazira (Upper Mesopotamia), the plains and the desert region. Iraq's climate is semi-tropical, arid and continental, with dry, hot summers and dry, cold winters. Average annual rainfall in the north-east is 800 mm, while in the middle and south it is around 150 mm.

Water resources are mainly attributed to the two rivers: the Tigris and the Euphrates. The share of ground water in meeting total water demand is insignificant. Average total river water resources of the country have been estimated as follows:

Tigris at Fatha	43.00 billion m^3
Euphrates at Hit	30.00 billion m^3
Adhaim River at Enjana	0.71 billion m^3
Diyala at Sudour	5.80 billion m^3

At present, the Tigris' flow is natural, except for its tributaries which are regulated by the Dokan Reservoir (the Lesser Zab) and the Derbendi-khan and Hemrin reservoirs (Diyala). The Euphrates is regulated by the Keban reservoir (Turkey), the Tabaqa reservoir (Syrian Arab Republic), and the Habbania and Qadissiya reservoirs in Iraq.

Surface water, the Tigris and the Euphrates, is the main source of water in Iraq. Ground water is an essential source of supply in desert areas, Jazirah and the foothills. It is brackish in most regions. The water quality is generally acceptable for domestic use and irrigation, but generally contains minerals. The most severe problem is salinity, which occurs over the whole Mesopotamia plain up to the Tharthar Lake (see figure 11). The main productive aquifers exist in fissured limestone of the Cretaceous period. Other aquifers such as Palaeocene-Eocene formation, Eocene, Euphrates, Lower Fars (Middle Miocene age), Upper Fars (Upper Miocene age), Pliocene-Pleistocene and alluvial quaternary, are of variable productivity and quality (6). Brackish water desalination has only been introduced on a small scale, which is of particular importance in respect to the vast region of Mesopotamia. However, different sources indicate that water desalination in Iraq reached to 5.54 Mm^3 in 1984.

Table 12 includes technical data on water wells in different parts of the country, as at 1978.

Table 12. Iraq's water well data in different parts of the country

Data	Zone Northern	Central	Southern	Total
Number of wells	671	789	29	1498
Depth (m)	10-339	10-481	17-203	10-481
Water level (m from ground)	1.5-63	Flowing to 207	1.2-15	Flowing to 207
Dynamic level (m)	13-138	Flowing to 290	1.2-84	Flowing to 290
Well yield (m^3/h)	1.14-263	1.1-177	2.18-18.2	1.1-263
Salinity (ppm)	190-9,950	246-10,000	1400-10,000	190-10,000

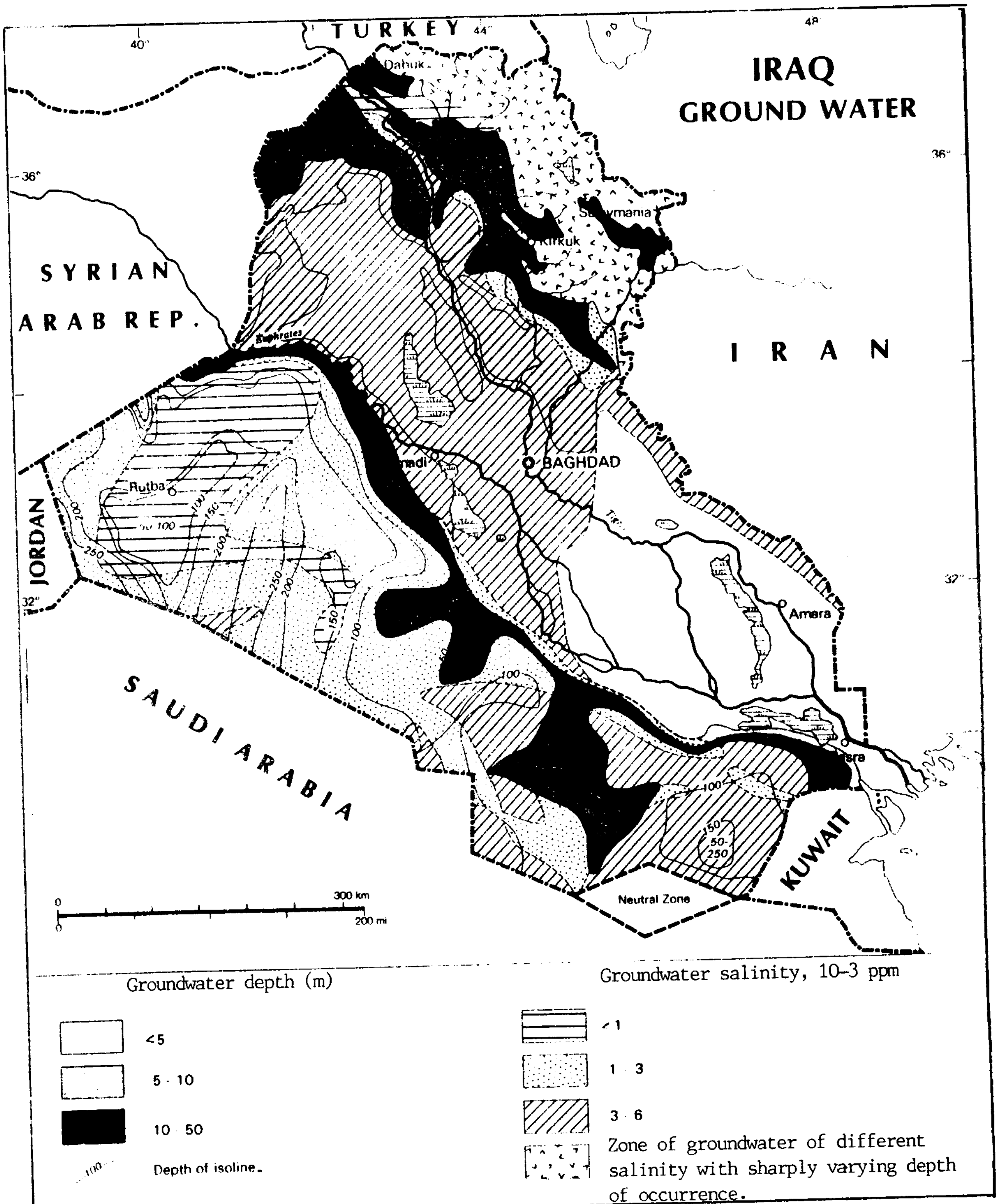
Source: United Nations, Department of Technical Co-operation for Development, Ground Water in the Eastern Mediterranean and Western Asia, Natural Resources, Water Series No. 9 (New York 1982). (United Nations publication, Sales No. E.82.II.A.8).

5. Jordan

Jordan's Five-Year Plan for economic and social development (1986-1990) indicates that the country's water supply consists of conventional water resources, ground water and surface water. Average annual rainfall ranges from 600 mm to 50 mm or less; average annual rainfall is about 6,000 Mm^3 in addition to 2,000 Mm^3 that falls in catchment areas outside Jordanian territories. The estimated average annual volume of surface water resources in Jordan is: 878 Mm^3 as surface water and 222 Mm^3 as ground-water aquifers (see table 13). Total quantities developed in 1985 from various sources reached about 520 Mm^3 and were used for different purposes:

Domestic and industrial	111 Mm^3
Irrigated agriculture in Ghor areas and Wadi Araba	309 Mm^3
- Irrigated agriculture outside Ghor areas	100 Mm^3
Total	520 Mm^3

Figure 11. Iraq's ground-water salinity



Source: United Nations, Department of Technical Co-operation for Development, Ground Water in the Eastern Mediterranean and Western Asia, Natural Resources, Water Series No. 9 (New York, 1982). (United Nations publication, Sales No. E.82.II.A.8).

Table 13. Jordan: summary of aquifer characteristics

ERA	PERIOD	EPOCH	GROUP	FORMATION OR STAGE: WEST BANK	FORMATION OR STAGE: EAST BANK	Thickness (m)	WATER YIELD POTENTIAL	LITHOLOGICAL DESCRIPTION
CENOZOIC	QUATERNARY	RECENT	JORDAN VALLEY	ALLUVIUM	ALLUVIUM	0-300	Poor-excellent	Gravel, sand, clay
CENOZOIC	QUATERNARY	PLEISTOCENE	JORDAN VALLEY	LISAN	LISAN	0-300	Poor-good	Calcareous clays and gravels
				SAMRA	SAMRA	0-300	Poor	Calcareous-reddish clays and gravels
CENOZOIC	TERTIARY	PLIO-MIOCENE	JORDAN VALLEY	NEOGENE	NEOGENE		Poor	Conglomerate, indurated
CENOZOIC	TERTIARY	OLIGOCENE ?	BELQA	BASALT AND CONGLOMERATE	BASALT AND CONGLOMERATE	100	Moderate-good	Basalt and conglomerate
CENOZOIC	TERTIARY	EOCENE PALEOCENE	BELQA	EBAL GERIZIM	FALEJ (B4)	300	Moderate-excellent	Limestone, marl, chert, chalk
				NABLUS	RAMTHA or	190	Poor	Limestone, chalk
MESOZOIC	CRETACEOUS	UPPER: DANIAN MAESTRICHTIAN	BELQA	KHANAHMAR ZARQA	MUWAQQAR (B3)	250	Moderate	Marl, chert, shale
MESOZOIC	CRETACEOUS	UPPER: CAMPANIAN	BELQA	AMMAN	AMMAN (B2)	100-150	Moderate-good	Limestone, chert, marl
MESOZOIC	CRETACEOUS	UPPER: SANTONIAN CONIACIAN	BELQA	ABU DIS	RUSEIFA (B1)	10-250	Poor	Chalk, marl and chert limestone
MESOZOIC	CRETACEOUS	MIDDLE: TURONIAN	AJLUN	JERUSALEM	WADI SIR (A7)	70-200	Good	Limestone, sandstone, marl
MESOZOIC	CRETACEOUS	MIDDLE: CENOMANIAN UPPER	AJLUN	BETHLEHEM	SHUEIB (A5-6)	70-150	Poor-moderate	Limestone, marl
MESOZOIC	CRETACEOUS	MIDDLE: CENOMANIAN MIDDLE	AJLUN	HEBRON	HUMMAR (A4)	30-200	Good-excellent	Dolomite limestone
				YATTA	FUHEIS (A3)	80-150	Poor-aquiclude	Marl, chalk, limestone
MESOZOIC	CRETACEOUS	MIDDLE: CENOMANIAN LOWER	AJLUN	BEIT (UPPER)	NAUR (A2)	120-300	Good	Limestone, marl, chalk
				KAHIL (LOWER)	(A1)	300	Excellent	Dolomitic limestone, marl
MESOZOIC	LOWER ? JURASSIC ?			KURNUB	UPPER KURNUB	200	Poor	Fine sandstone, shale, limestone
					LOWER KURNUB	110	Moderate-good	White, coarse sandstone
MESOZOIC	TRIASSIC			ZARKA	UPPER ZARKA	300	Good	Limestone dolomite, sandstone
					LOWER ZARKA	70	Poor	Shale, gypsum, marl
M A J O R U N C O N F O R M I T Y								
PALEOZOIC	SILURIAN ORDIVICIAN (UPPER)				KHREIM	0-400	Poor	Fine-grained sandstone, mudstone and shale
PALEOZOIC	ORDIVICIAN (MIDDLE) CAMBRIAN (LOWER) (LOWER)				DISI	250 130-350 190-350	Good	Bedded Brown Massive White Massive Brown Medium to coarse grained sandstone
PALEOZOIC	CAMBRIAN (LOWER)				UM SALEB	50-60	Moderate	Arkosic sandstone
	PRE-CAMBRIAN				AQUABA	..	Poor	Granite and diabase

Source: Data compiled by John W. Harshbarger from published and unpublished reports in the files of the Natural Resources Authority and of the United Nations Development Programme, Amman, 1966

Table 14. <u>Ground-water resources in Jordan</u>

Basin	Available quantity (Mm^3/yr)	Total dissolved solids (ppm)	Average water well depth (m)	Static water level (m BGL)	Average water well yield (m^3/hr)	Remarks
Yarmouk	80	300-800	150-350	100-280	20-120	
Zerqa River	30	350-1,200	150-400	20-250	50-200	Brackish in some parts of the basin
Azraq Basin	20	290-360	25-250	5-75	20-180	
Jordan Valley and the Heights	54	500-2,500	100-300	25-80	50-250	Brackish in some parts of the valley
Dead Sea Basin	60	500-1,000	200-250	50-100	80-150	Brackish in some parts
Wadi Araba and Southern Ghors	23	800-3,000	50-300	25-80	50-150	Brackish in many parts of the wadi
Wadi Araba Heights	12	...	...	...	...	...
Disi-Al-Mudawara	50	250-300	300-45	70-90	200-300	
Al-Jafr-Al Shaziya	20	500-3,500	100-400	40-100	20-120	Brackish in some parts of Al Jafr and Al Shaziya
Wadi Sirhan-Al-Hamad	27	100-2,500	250-350	100-200	40-50	Brackish in many parts of the wadi
Northern Desert	32	500-1,000	300-400	150-250	100-250	

<u>Source</u>: O. Jouda, "Water resources utilization in Jordan", paper presented at the ACSAD-AFESD-KFAED Workshop on Water Resources Utilization in the Arab World, Kuwait 17-20 February 1986, p. 18 (in Arabic).

<u>Note</u>: ... Data not available.

Generally, surface water quality is very good. Ground water in some parts of the Jordan Valley and in the eastern and south-eastern desert, together with the irrigation return flow contains fairly large amount of salt. Though brackish water sources exist in different parts of Jordan, they remain unassessed. Table 14 indicates the major ground-water basins in Jordan and their hydrogeological characteristic (7).

6. Lebanon

The total annual precipitation over the country is about 9,700 Mm^3, of which 4,025 Mm^3 is surface water and 600 Mm^3 is recharged to aquifers, while the remainder is lost by evapo-transpiration and submarine seepage. The total annual estimated volume of water resources is 1,100 Mm^3 (surface and ground water), in addition to 690 Mm^3/year as baseflow. Domestic water supply relies mainly on ground water, of which about 75 per cent comes from springs and 25 per cent from wells. Lebanon's available water resources are sufficient to meet all of its present uses, and those of the near future. The quality of water in shallow aquifers is generally good (200-400 ppm). Salinity increases towards the coast, owing to minor sea water intrusion (1,000-3,000 ppm). The deeper aquifers produce water of 3,750 ppm (6).

7. Kuwait

Kuwait is a dry country with hot, dry summers and mild winters. The air temperature fluctuates between 52° C in July to August (maximum) to a few degrees below freezing in December, January and February. Relative humidity ranges between 85 per cent as a maximum average, normally in January, and 12 per cent as a minimum average in the summer months. Most of the rain falls between the months of November and March, and varies from year to year: in some years it in as low as 24 mm (1964) and as high as 260 (1961). The average annual rainfall is around 140 mm. The average annual evaporation at the International Airport is about 15.5 mm/day. The main water supply source is ground water. Aquifer characteristics in Kuwait are summarized in table 15 (8), (9), (10).

Table 15. Kuwait's aquifer characteristics

Geological age	Location	Water conditions	Transmissivity (m^2/day)
Pleistocene	Rawdhatain, Umm Al Aish	Fresh Fresh	450-900
Middle Eocene	Salibiya	Brackish	75-225
Middle Eocene	Shagaya	Brackish	150-750
Middle Eocene	Wafra	Brackish	75-1,200

Source: Compiled from data supplied by Kuwait, the Ministry of Electricity and Water, and ESCWA calculations.

Table 16 gives the different locations, yield capacities and quality of available ground-water well fields in Kuwait. It can be seen that these waters are mostly brackish, with the exception of the El-Rawdhatain and Umm Al Aish Field wells (see figure 12).

The current use of ground water obtained from well fields 1 to 8 (see table 16) is mainly for municipal and industrial purposes, while locations 9 and 10 are used for irrigation. There is a continuous drop in static water levels and a deterioration in water quality. Brackish water is currently blended with desalinated distilled sea water - by 7 to 20 per cent - and this is used for different domestic uses at an estimated daily rate of 227 x 10^3.

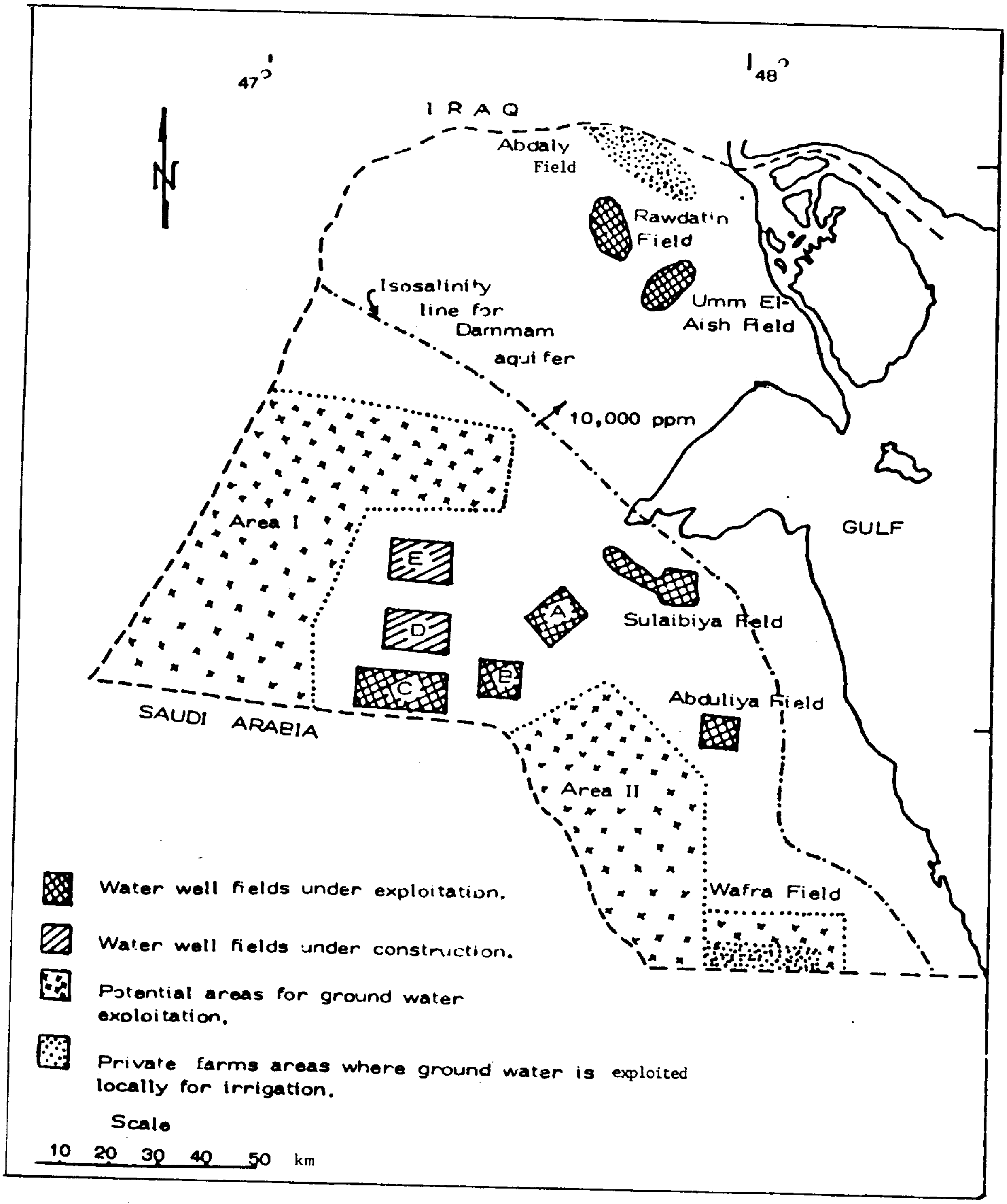
A decline in the water-table is taking place in Kuwaiti water-bearing formations, and equilibrium between natural recharge and ground-water attraction is not possible owing to the huge withdrawal of ground water. Accordingly, salinity is increasing as a result of heavy pumping over time (8),(9), (10).

Table 16. Main ground-water fields in Kuwait

No.	Location	Geological formation	Yield capacity (m^3/day)	TDS ppm	Uses
1.	Al Salibiya	Dammam	94.6	4,500	Domestic and irrigation
2.	Al Abdali	Dammam	30.0	4,500	Kuwait Oil Co.
3.	Umm al Aish	Kuwait, Dabdaba	9.5	1,500	Domestic
4.	Al Rawdhatain	Kuwait, Dabdaba	7.5	700	Domestic
5.	Al Shagaya (A)	Kuwait, Dammam	19.0	3,500	Domestic and irrigation
6.	Al Shagaya (B and C)	Dammam	106.0	3,500	Domestic and irrigation
7.	Al Shagaya (D)	Dammam	45.4	3,000	Domestic and irrigation
8.	Al Shagaya (E)	Kuwait, Dammam	57.0	3,500	Domestic and irrigation
9.	Al Wafra	Kuwait	114.0	5,500	Irrigation
10.	Al Abdali Farm	Dabdaba	114.0	4,800	Irrigation

Source: Compiled from data supplied by Kuwait, Ministries of Water and Electricity and the Ministry of Agriculture and Fisheries.

Figure 12. Water well fields and areas of actual and potential ground-water exploitation



Source: Data supplied by Kuwait, Ministry of Electricity and Water.

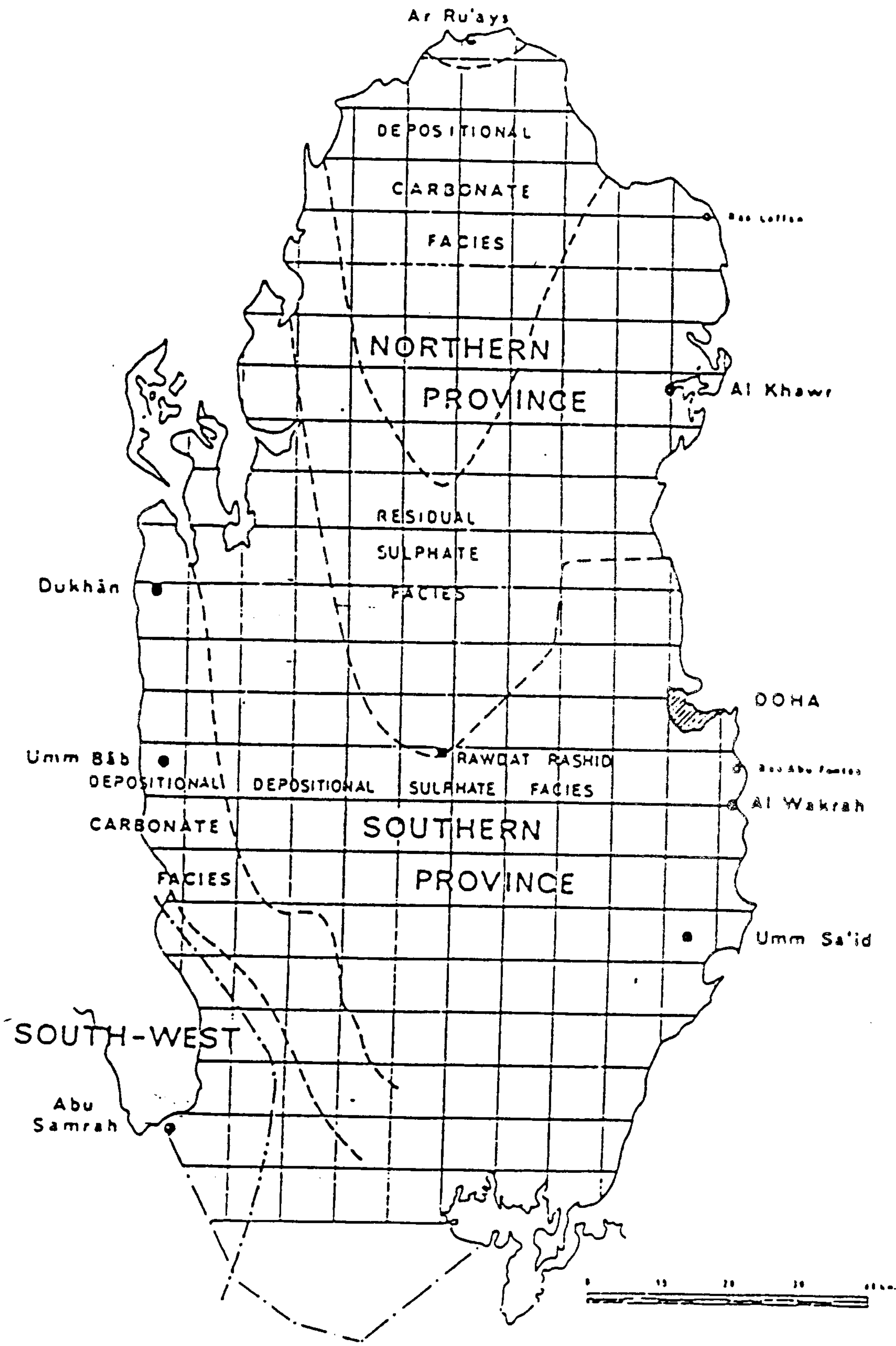
8. Qatar

Qatar is a peninsula that protrudes northwards from the eastern coast of Saudi Arabia into the Gulf. Qatar's water supply is derived from desalinated sea water, ground water and treated sewage effluent. Rainfall is low, irregular and variable, ranging from less than 25 mm to more than 90 mm. Summers are characterized by high temperatures and humidity. Winters are mild, with temperatures of around 21° C or less.

Until 1953, Qatar largely depended on ground water to meet domestic and agricultural demand. Hand-dug wells were in common use in some areas. As demand for water increased, additional water resources were sought through sea water desalination. The Doha (capital) desalination plant (680 m^3/day) for example, raised the desalination capacity to 264,000 m^3/day (96 Mm^3/year) in 1986.

Ground-water resources in Qatar are used for both domestic and agricultural purposes. The country has traditionally depended on the ground water extracted from three water aquifers at Umm Er Radhuma, Rus and Dammam (see figure 13). The lower Rus and upper Umm Er Radhuma aquifer (see table 17) are hydraulically connected, and their relative salinity is low (>3,000 umhos). This renders the water adequate for domestic use (41.25 M), while the other part of the aquifers is considered to have high salinity (3,000 to >10,000 umhos), hence it is released for agricultural purposes (2,194 Mm^3). Figure 14 shows water quality in terms of electrical conductivity over Qatar. Almost all of the fresh ground water reserves lie in the Rus and Umm Er Radhuma aquifers in the northern part of Qatar. Rus water quality is less than 1,000 ppm TDS and is used for drinking purposes. Umm Er Radhuma aquifer quality is poorer than Rus (>1,000 ppm), and the water is exploited for agricultural purposes. Ground water use between 1964-1984 is illustrated in figure 15. The estimated quantity of ground water currently extracted from all aquifers for agricultural purposes is more than 100 Mm^3/year. Renewable water (recharge) is calculated at 28 Mm^3/year. It is estimated that the northern ground-water body is being over-extracted to the extent of 50 to 85 Mm^3/year. No further development of ground water is possible because of the present over-extraction of ground-water reserves that causes an upward movement of brackish ground water and lateral sea water intrusion. It is expected that water quality will reach unusable limits by the year 2000. Accordingly, domestic users and industrial development will have to depend on sea and brackish water desalination, as well as treated sewage effluent (11), (12).

Figure 13. Qatar's main ground-water areas



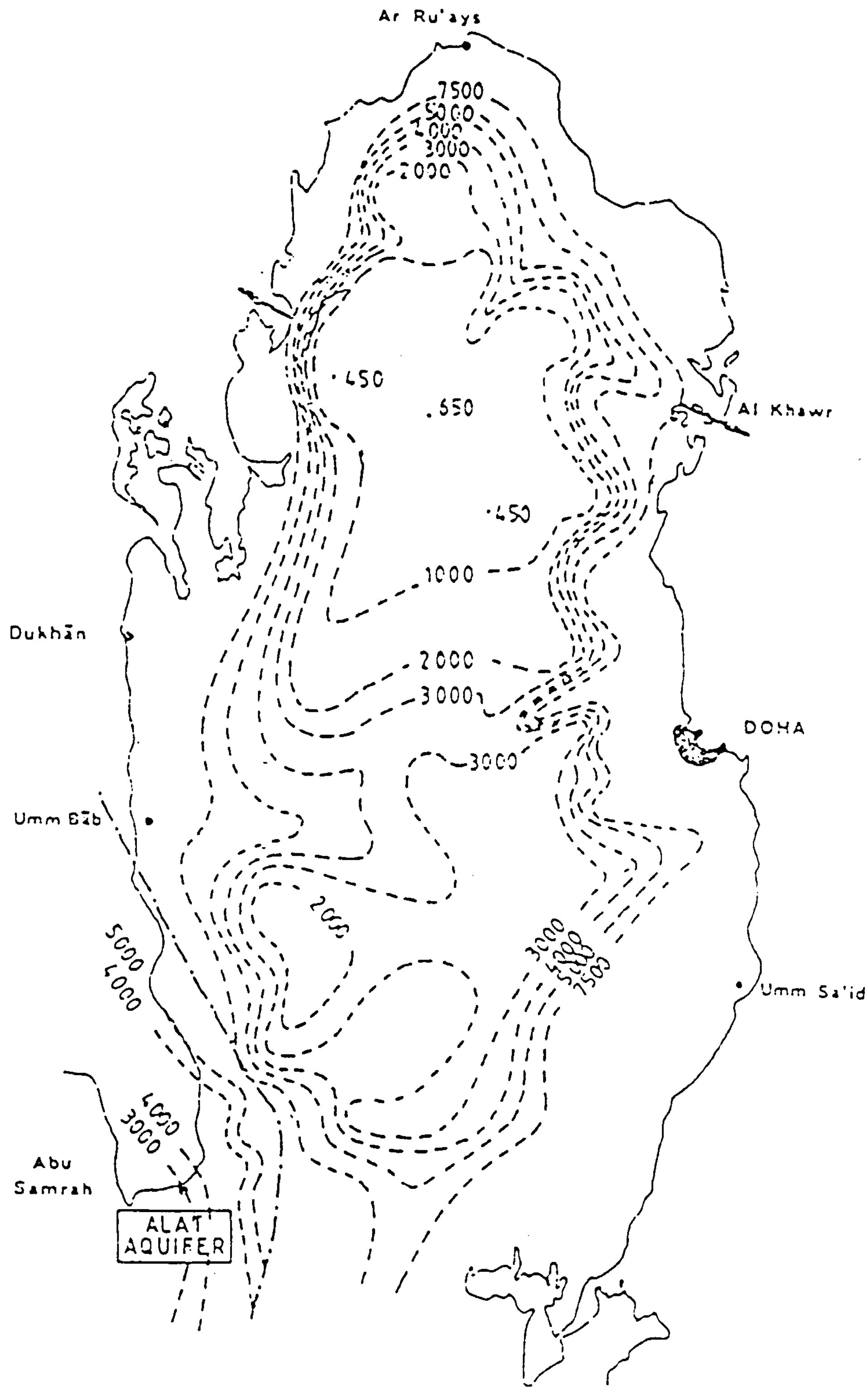
Source: Data supplied by Qatar, Ministry of Electricity and Water.

Table 17. Stratigraphy of Qatar

Age	Formation	Sub-formation	Number	Thickness (m)	Lithology	Equivalent in Saudi Arabia	Thickness in Saudi Arabia	Hydrogeological significance
Miocene-Pliocene	Hofuf			?	Sandy marl and sandy limestone	Hofuf	95	
Middle Miocene	Dam	Upper Lower		50 30	Marl, shale sub-ordinate sandstone	Dam	91	Aquiclude
Middle Eocene	Dammam	Upper	Abarug	10	Dolomitic limestone and marl	Alat		Important aquifer at Abu Samra
			Simsima	30	Dolimites and limestones	Khobar	35	Important aquifer where phreatic levels are near surface in the coastal belt
		Lower	Alveoline	1	Limestone	Alveoline		
			Midra Shale	5	Shale and marl	Saila an Midra		
			Fhaihil Limestone	1	Limestone			
Lower Eocene	Rus			28-44	Dolomite limestone with thick bands of gypsum	Rus	56	Carbonate facies is an important aquifer
Palaeocene	Umm er Radhuma			300	Dolomites with bands of chert, marl and clay	Umm er Radhuma	243	Upper unit is an excellent aquifer

Source: Data supplied by Qatar, Ministry of Electricity and Water.

Figure 14. Electrical conductivity of ground water, 1980
(umhos)



Source: Data supplied by Qatar, Ministry of Electricity and Water.

Figure 15. Qatar's ground water use, 1964-1984

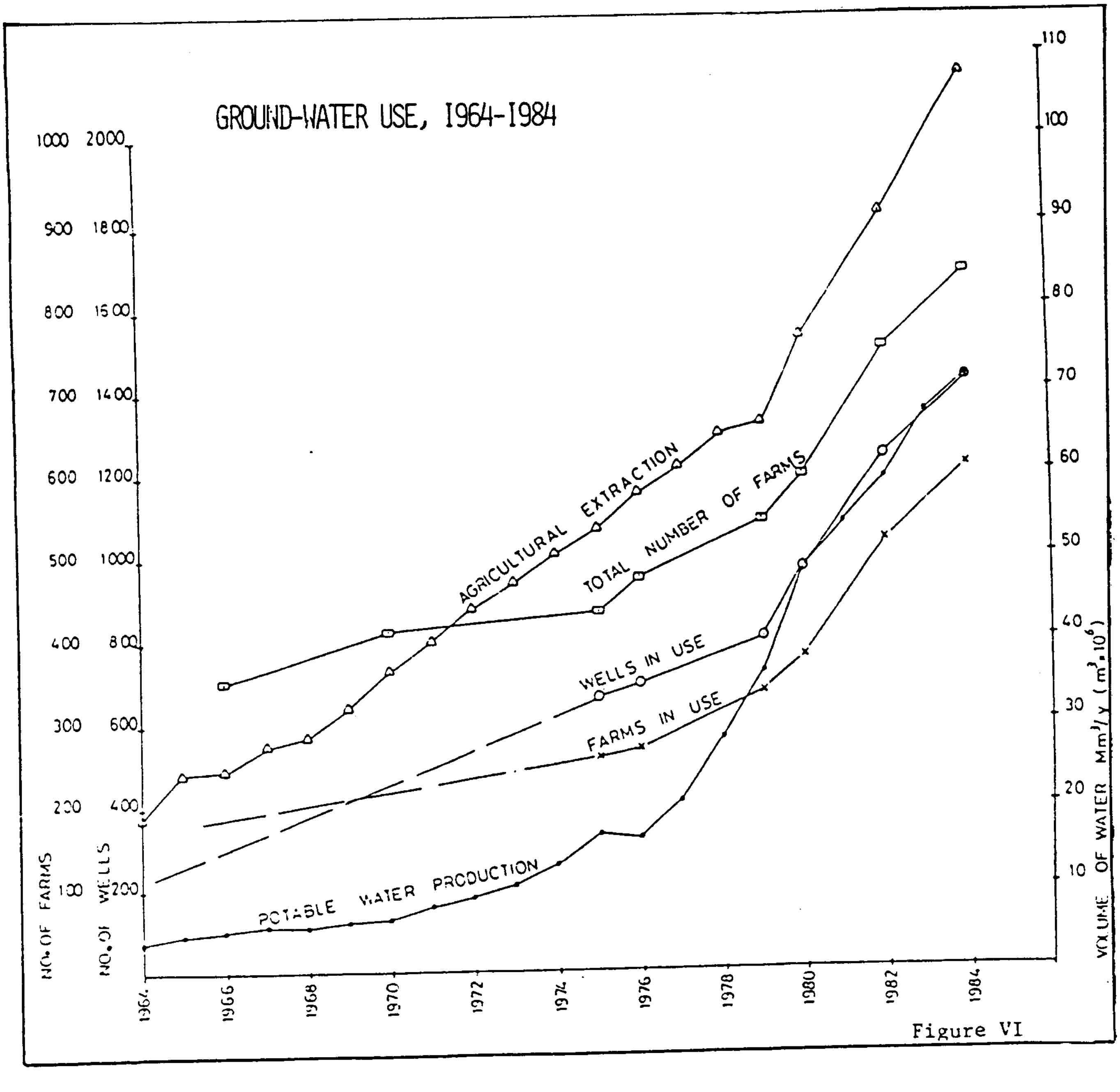


Figure VI

Source: Data supplied by Qatar, Ministry of Electricity and Water.

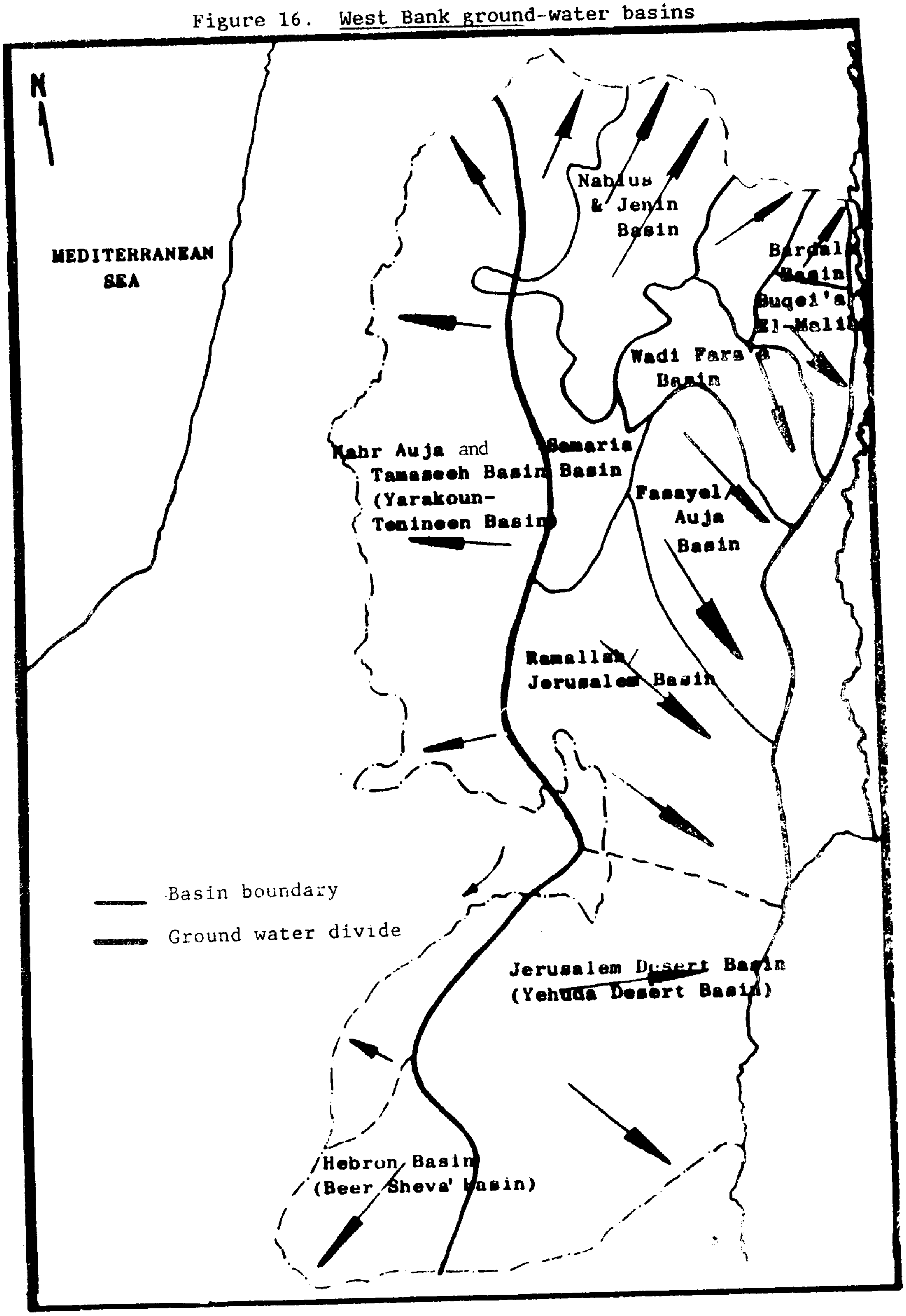
9. West Bank and Gaza Strip

A reliable supply of water for both domestic and agricultural use is a prerequisite for social and economic development on the Western Bank and Gaza Strip. Precipitation in the form of rainfall and sometimes snow is the direct source of all fresh water in the area, but this is insufficient to meet the potential water needs of the occupied territories. The average annual rainfall varies between 450 to 600 mm in the mountainous and northern areas of the West Bank, to 150 mm in the Jordan Valley. In Gaza, the average annual rainfall is 370 mm in the north and 220 mm in the south, with an overall average of 275 mm. Evaporation is an important factor, since 70-75 per cent of total annual precipitation is lost to the atomosphere by either evaporation or transpiration, which ranges from 1,900 mm per annum on the western slopes to 2,600 mm on the Dead Sea shore. In the Gaza Strip, the mean annual evaporation is between 1,800 to 1,900 mm. Run-off varies between 7 and 14 per cent of annual rainfall. Moreover, total surface waters in the West Bank are estimated to be between 120 and 200 Mm^3/yr, depending on annual rainfall. It is estimated that the run-off from the western drainage basin to some of the seasonal rivers averages 20-25 Mm^3/yr. The Wadi Fara'a baseflow, which is fed by a number of springs (the largest being Fara'a, Al-Beidan and Ein Al-Miska), has a continuous flow all year around, but the remaining wadis are ephemeral. Total surface run-off from the whole of the West Bank (both western and eastern basins) is 40-50 Mm^3/yr. This significant amount of surface water urgently requires an efficient system of water conservation if it is to benefit the population on the West Bank.

In contrast to the West Bank, there are no continuous surface water resources in the Gaza Strip. Wadi Gaza crosses the strip between Gaza City and Deir Al-Balah. At present, all run-off water in this seasonal river flows to the sea, but there is a need to conserve it as this source of fresh water is needed to recharge the shallow ground-water resources and to decrease its salinity.

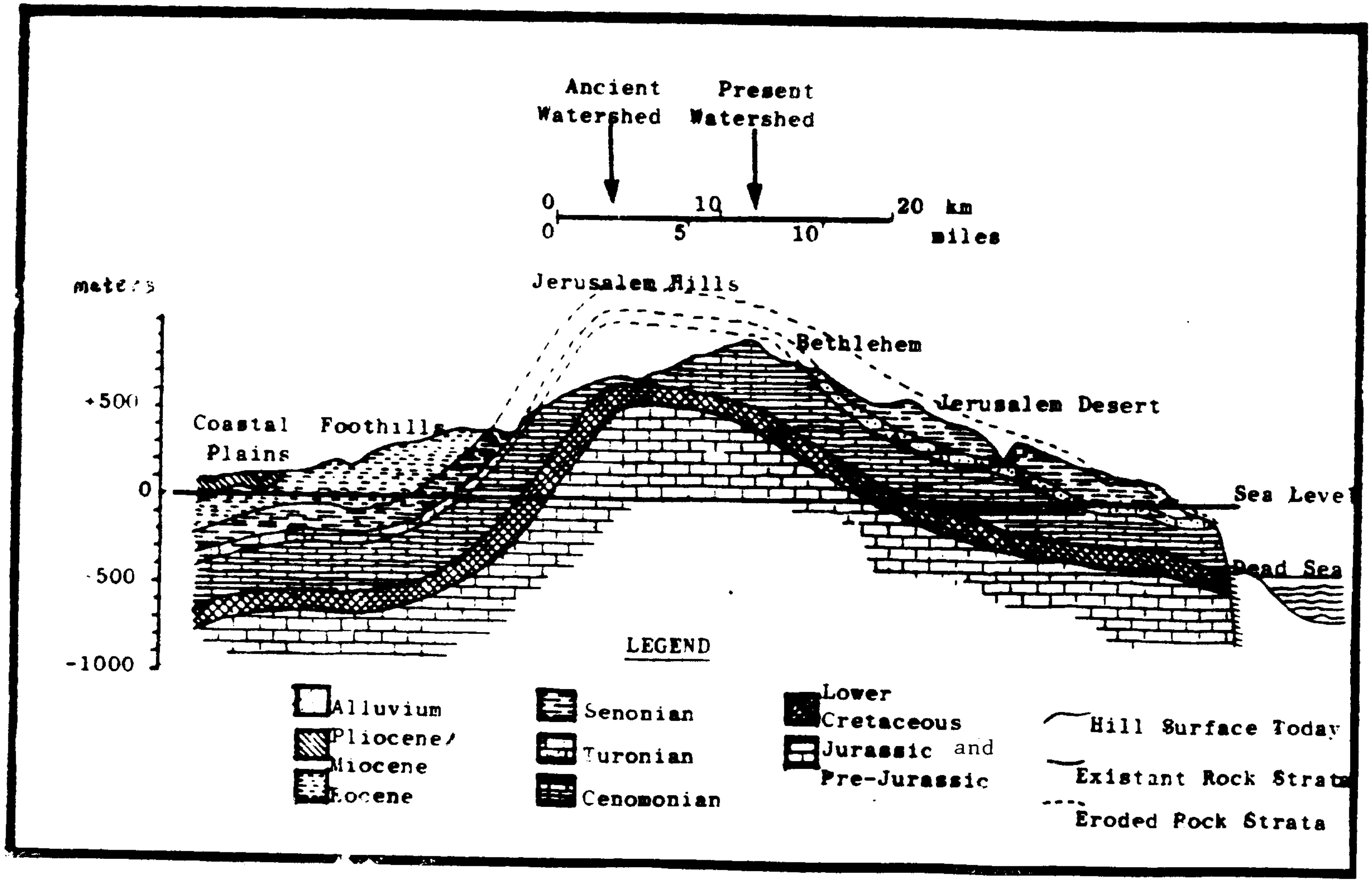
The potential supply of ground water in the West Bank aquifer, i.e. for recharge and storage, has been estimated at up to 710 million cubic metres. The West Bank ground-water basins are illustrated in figure 16. In normal circumstances, the water retained under ground is 600 Mm^3. About 55 per cent of it occurs in the western part of the West Bank, while the remainder is mainly located in the eastern part. This ground water potential includes up to 60 Mm^3 of brackish water that is present on the eastern side of the West Bank. In the Gaza Strip, the total recharge to the system from all sources is estimated at only 75 Mm^3 per year. Figure 17 gives a diagrammatic sketch of a cross-section of West Bank (through Beth Lahem), showing surface watersheds and rock strata (13).

Figure 16. West Bank ground-water basins



Source: United Nations, Economic and Social Commission for Western Asia (ESCWA), Food Security in the West Bank and Gaza Strip (October 1985) (ESCWA/AGR/85/4).

Figure 17. Diagrammatic sketch of cross-section of West Bank (through Bethlehem) showing surface watersheds and rock strata



Source: United Nations, Economic and Social Commission for Western Asia (ESCWA), Food Security in the West Bank and Gaza Strip, (October 1985) (ESCWA/AGR/85/4).

10. Oman

Oman occupies the south-east of the Arabian peninsula with an area of 213,000 km^2. Rainfall varies from one place to another, as well as over time. In Muscat, annual rainfall averages 107 mm, while in Sohar it is 38 mm, and about 115 mm in Dhofar. In spite of the arid climate, water is plentiful in many of the incised wadis of the mountains, and is also present beneath the surrounding plains. Run-off in the mountains is high owing to the low permeability of the rocks along the wadis, which results partly in flows, while the remainder infiltrates the wadi gravel and sands and is released as a perennial baseflow. Northern Oman and Dhofar receive most of the country's precipitation, which contributes to ground water recharge. The total estimated volume of surface run-off and ground water recharge is about 1,409 Mm^3/yr.

Ground water in Oman is derived from deep aquifers, recent wadi deposits, alluvial fans and coastal plains along the mountain ranges. Most of the extraction takes place via shallow aquifers from three major regions, as is indicated in table 18, which illustrates the general geological stratigraphy and hydrogeology of Oman's different regions. These can be described as follows (14):

(a) Batinah plain

The aquifer system exists in alluvial deposits of general thickness ranging from 30 to 40 m. Intensive pumping has resulted in sea water intrusion, and in turn salinity has increased tremendously.

(b) Oman mountains and interior plains

In this region, ground water accumulates in the narrow bottoms of the deeply incised valleys that form line sinks for ground-water discharges from the hills in the form of springs, baseflows or *falajs*. Ground water on the interior plains exists in 10 m thick coarse clastic materials that overlay the clay deposits. Total dissolved solids in the ground water fluctuates between 300 and 2,000 ppm

(c) Dhofar

Ground water occurs in carbonate rocks and conglomerates. Water quality is generally poor and brackish. The region is still being developed.

Estimates of conventional water resources in Oman in the different regions are shown in table 19.

11. Saudi Arabia

Saudi Arabia has an area of 2,149,000 km^2 and occupies most of the Arabian peninsula. The latter may be divided into six physiographical units (6):

(a) Mountain plains (wide gravel plains and numerous granite inselbergs of the shield);

Table 18. Oman's general stratigraphical-hydrogeological data

Age			Litho-stratigraphy		Aquifer potential
Quaternary	Holocene Pliestocene Pliocene		Terestial deposits: conglomerate, sand and ground with clastics and eolian sand and silt		Main aquifer, good water quality in Batinah, Dhahir and Sallalah plain
Tertiary	Miocene		Marls and clays with evaporites		Aquiclude
	Oligocene		Marls, limestone and massive limestone		Fair
	Eocene Faleocene	Upper Middle Lower	Dammam: marls limestone RUS: limestone, cherts gypsiferon Umer Radhuma		Fair quantity and quality Good potential in Dhofar
	Uncertain Probably Upper Cretaceous		Semail Mappe: basic and ultra basic rocks		Fair if fractured Good potential in Dhofar
	Uncertain		Hawasinah group: conglomerate Calcareous, Quartz sandstone, limestone, conglomarate limestone, shales and radiolarites		Offers fair aquifer if fractured
Mesozoic	Cretaceous	Upper Middle Lower	Figu, Muti, and Qumayrah: Wasia) Hajar super group: Kahmah)	shales and limestone limestone : limestone and shales	No potential Fair to good
	Jurassic		Sahtan group	Shales and limestone	No potential
	Triassic Dermian		Mahil formation Saiq formation	Dolomite Dolomite	

Source: United Nations, Economic Commission for Western Asia, Assessment of Water Resources in the ECWA Region, (Beirut, January 1981), p. 152 (E/ECWA/NR/L/1/Rev.1).

Table 19. Oman's conventional water resources

Water basins	Surface water (Mm^3/yr)	Available ground water (Mm^3/yr)	Water use (Mm^3/yr)
Ras Musandam	23.4	18.0	12.0
Batinah plain (east and middle)	180.2	105.5	147.4
Batinah plain (north)	168.1	119.0	121.6
Al-Dhahira (interior northern basins)	121.7	58.8	16.6
Oman interior	143.2	75.1	48.7
Eastern region	95.9	70.8	29.2
Qurayat and Sour	90.1	26.9	15.4
Mullala and southern wadis	67.9	52.8	16.3
Dhofor and northern wadis	27.3	27.0	-
Total	917.8	563.9	407.2

Source: Data compiled by ESCWA.

(b) Escarpment belt (Tuwaiq mountain scarp);

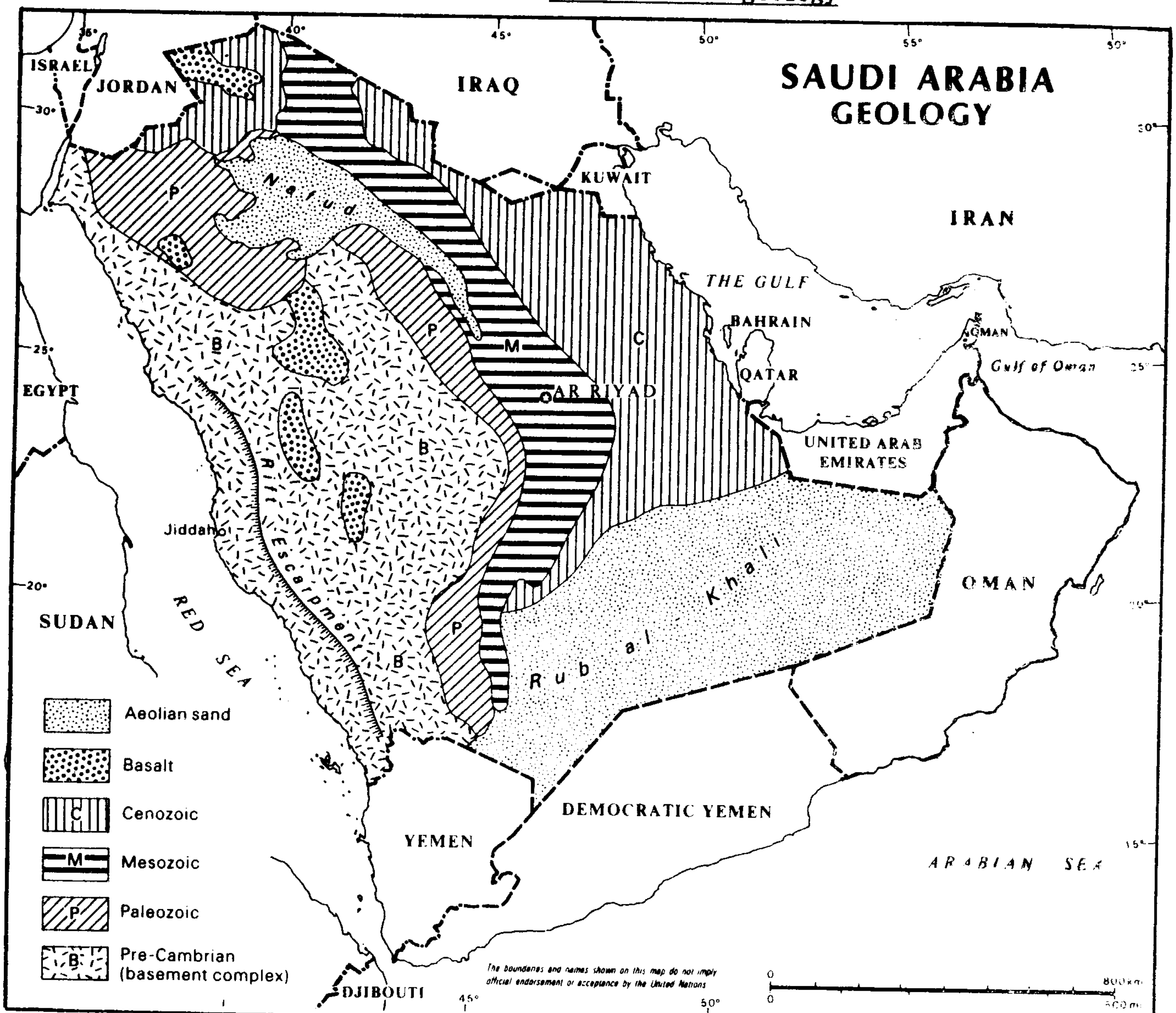
(c) Central plateau (tertiary sediment between the escarpment belt and coastal plain);

(d) Gulf coastal plain (sabkhahs, thin gravel plain, and small marine terrace);

(e) Aeolian sand area, covering approximately half of the peninsula; Rub al Khali, the great Nafud, Ad Dahna and Al Jafura.

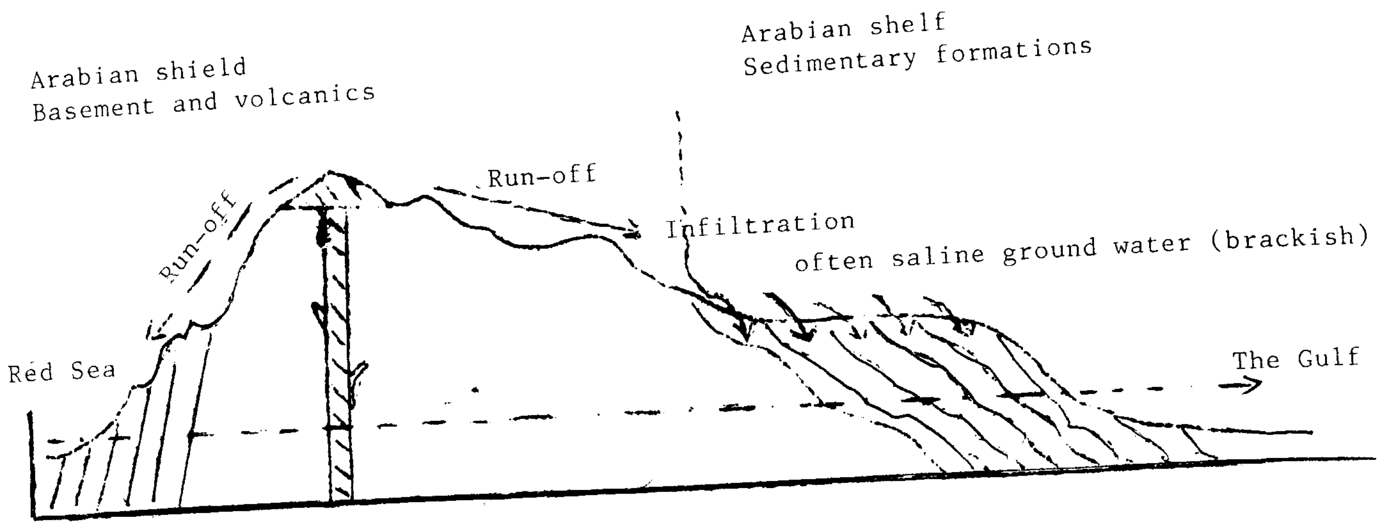
Saudi Arabia is a hot, dry country. The absence of surface water and the scarcity and irregularity of rainfall makes it highly dependent on ground water. In this respect, Saudi Arabia can be divided into three regions: the Tihama coast, the Arabian shield and the eastern Arabian sedimentary basin (figure 18). The latter can be subdivided into depleting and non-depleting aquifers. Depleting aquifers are those post-Jurassic aquifers which have a normal recharge and aquifer underflow and discharge regime, whereas non-depleting aquifers are pre-Cretareous aquifers which do not discharge, have no normal underflow regime and hence reject recharge. In this case the yield comes from storage, as in Riyadh, where water is pumped from the Minjur aquifer.

Figure 18. Saudi Arabia: geology



Source: United Nations, Department of Technical Co-operation for Development, Ground water in the Eastern Mediterranean and Western Asia, Natural Resources, Water Series No. 9 (New York 1982). (United Nations publication, Sales No. E.82.II.A.8).

Figure 19. Hydrogeological profile across Saudi Arabia



Source: United Nations Economic Commission for Western Asia, Assessment of Water Resources Situation in the ECWA Region, (Beirut, January 1981), p. 187, (E/ECWA/NR/L/1/Rev.1).

In the Tihama coastal region, ground water occurs in wadi fill and coastal plain sediments, which are thin, shallow and quick to respond to stream-flow. In this region, surface water is considered to be a good potential for the storage and recharge of thin aquifers. Brackish water of different salinities is encountered as a result of sea water intrusion. The Arabian shield region is a vast peneplain of broad shallow wadi beds, granite inselbergs, broad basalt harrats and aeolian sand. Ground water in the shield is restricted to the wadi bed alluvium, or to jointed or weathered zones of upper basement complex rocks that are crossed by wadis. The quality of water is good in wadi head-waters of the low TDS and bicarbonate type, while in the lower wadi reaches it is dominated by chloride and has increasing TDS that turn to brackish water (around 6,000 ppm).

The eastern Arabian sedimentary basin schematic hydrogeological section is shown in figure 20. Basin water quality is sulphate-chloride dominated in the depleting and perched aquifers along wadi courses, especially along the border with Iraq. TDS content is regionally consistent throughout the basin, though with some local anomalies, and is in the range of 3,000 mg/l above the Sabkhah line and 6,000 to 50,000 mg/l below it (see figure 21), which is considered to be brackish (6)(15). Table 20 shows the generalized hydrogeological section of Saudi Arabia.

12. Syrian Arab Republic

The Syrian Arab Republic can be divided into four hydrogeological regions (see figure 22). Lithology, geological structure and climate are the most important factors that define these regions. Several regional ground-water flow systems have been delineated. The lithostratigraphic sequence is illustrated in table 21. In the humid and semi-humid calcareous massifs of the western part of the country, a complex pattern of ground-water flows can be identified. Salinity levels are indicated in figure 23, where brackish ground-water zones are delineated.

A recent ESCWA study has shown that available ground water is estimated to be 1,625 Mm^3/year for domestic, agricultural and industrial purposes.

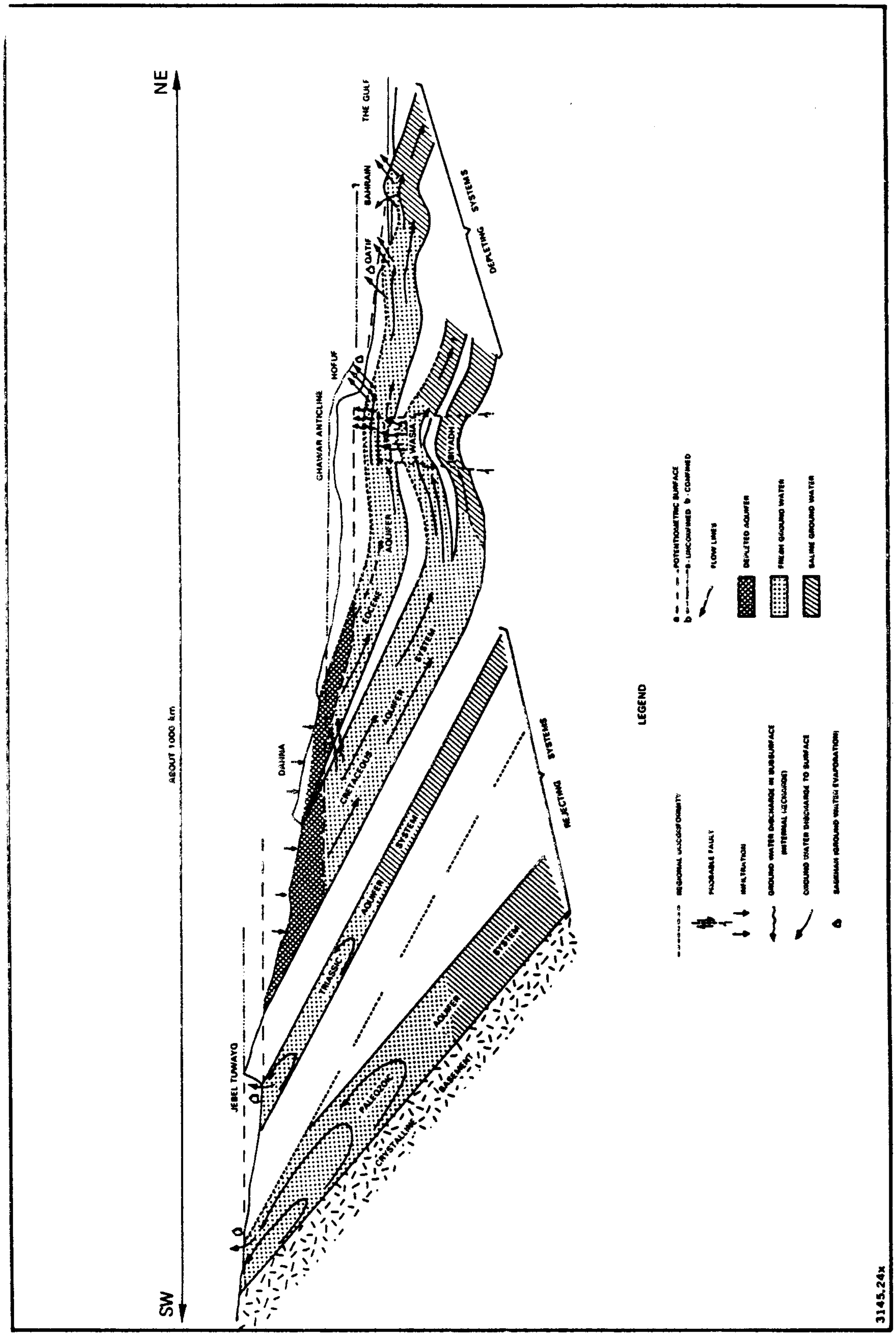
The average annual flow of perennial and intermittent rivers in the country is estimated to be 30 to 35 billion cubic metres (11).

In 1986, the quantity of water utilized in the Syrian Arab Republic had reached 7,200 mm^3 (surface and ground water), which was distributed as follows (11):

432 mm^3	For domestic use	(6 per cent)
288 mm^3	For industry use	(4 per cent)
6,480 mm^3	For irrigation	(70 per cent)
7,200 Mm^3	Total	

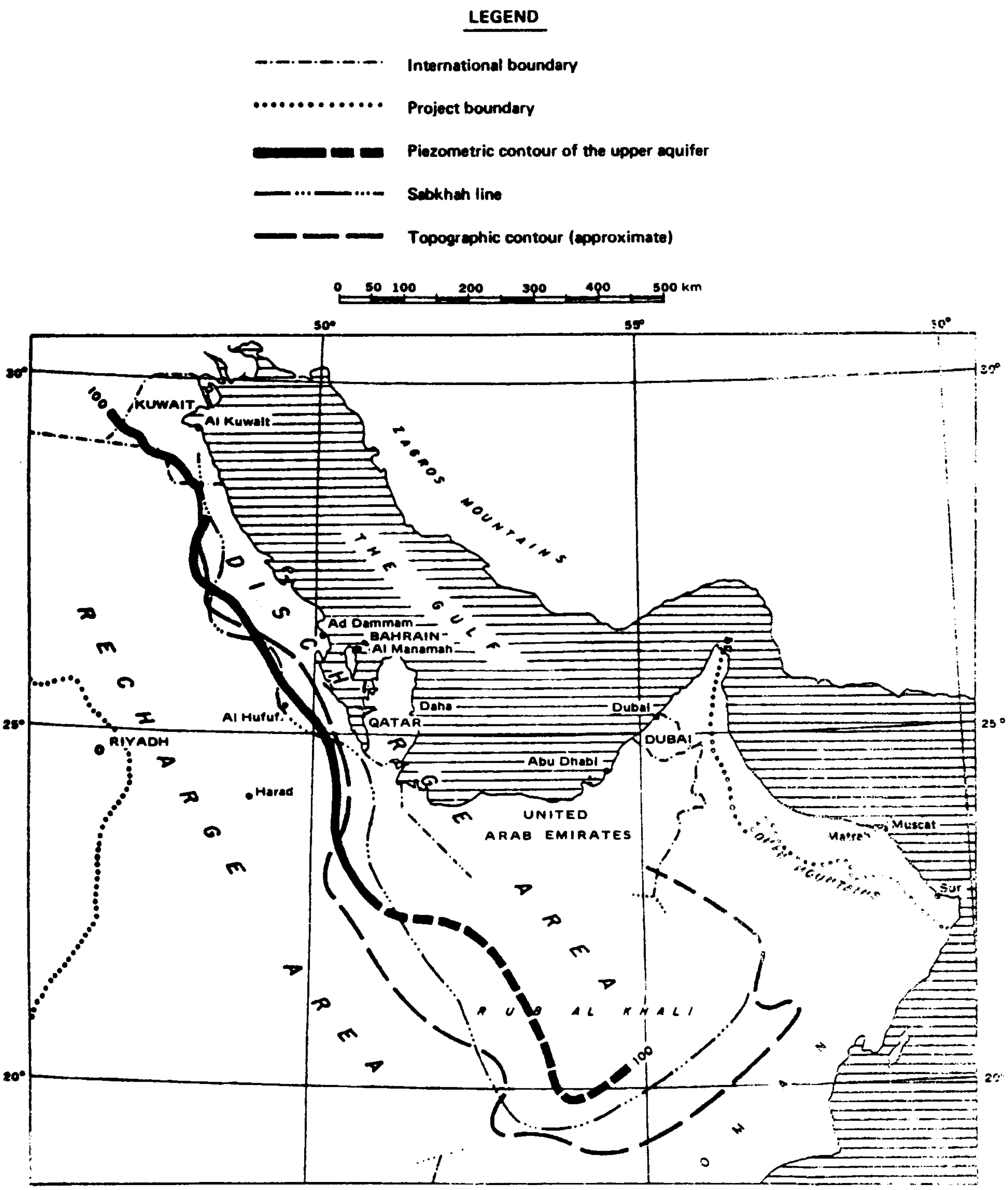
The estimates given in table 22 provide information about the relative importance of surface and ground-water resources in the Syrian Arab Republic, where ground water recharge and discharge in the different hydrogeological regions are indicated (6).

Figure 20. Saudi Arabia: schematic hydrogeological cross-section of the eastern Arabian sedimentary basin



Source: United Nations, Department of Technical Co-operation for Development, Ground water in the Eastern Mediterranean and Western Asia, Natural Resources, Water Series No. 9, (New York 1982) p. 128, (United Nations publication, Sales No. E.82.II.A.8).

Figure 21. Saudi Arabia: Sabkhah discharge/recharge lines



Source: United Nations, Department of Technical Co-operation for Development, Ground water in the Eastern Mediterranean and Western Asia, Natural Resources, Water Series No. 9 (New York 1982), p. 138, (United Nations publication, Sales No. E.82.II.A.8).

Table 20. Generalized hydrogeological section of Saudi Arabia

AGE				Formation	Generalized lithologic description	Thickness (type or reference section)	Aquifer Characteristics
CENOZOIC	Quaternary and tertiary			Surficial deposits & basalts	Gravel, Sand, Silt and Basalt		Produce variable quantity and quality of water depending upon recharge by rainfall, Basalt yields little water in western Saudi Arabia
CENOZOIC	Tertiary	Meocene and Pliocene		Kharj	Limestone, lacustrine Limestone, gypsum	28 M	Generally called Neogene aquifer. Irregular occurrences of water. Artesian and non-artesian conditions. Prolific aquifer in the areas of Hufuf, Wadi Miyah and some others in the eastern province
				Hofuf	Sandy marl, and sandy Limestone	95 M	
				Dam	Marl, Shale, Subordinate Sandstone	91 M	
				Hadrukh	Calcareous, Silty Sandstone	84 M	
		Eocene	Lutetian	Dammam	Limestone, Dolomite	35 M	Produces moderate amounts of water under artesian and non-artesian conditions.
			Yprersian	Rus	Marl, Chalky limestone	56 M	
		Paleocene	Thanetian	Umm er Radhuma	Limestone, dolomitic	243 M	One of the most prolific aquifers of the Kingdom, with high transmissibility that varies between 500,000 and 3 Mgd/ft
			Montian		Limestone		
MESOZOIC	Cretaceous		Maestrochtian	Aruma	Limestone	142 M	Yields little water with a low quality
			Campanian				
			Turonian	Wasia (Sakaka sandstone northwest Arabian)	Sandstone, Subordinate Shale	42-500 M	Low production or even dry near outcrop, very high productive artesian and non-artesian conditions in Eastern Province. Hydraulically interconnected with Riyadh near outcrops
			Cenomanian				
			Aptian	Biyadh	Sandstone Subordinate Shale	425-600	Moderately productive sandstone aquifer, hydraulically interconnected with wasia near outcrop.
			Barremian hauterivian	Buwaib	Biogenic calcarenite & calcarenite limestone	180 M	
			Valanginian	Yamama	Biogenic	46 M	

AGE			Formation	Generalized lithologic description	Thickness (type or reference section)	Aquifer Characteristics
MESOZOIC	Jurassic	Berriasian	Sulaiy	Chalkyaphanitic limestone	170 M	
		Tithonian	Hith	Anhydrite	90 M	Always yield mineralized water
		Kimmeridgian	Arab	Calcarenite, Calcarenite 8, aphanitic limestone	124 M	Yields little amount of water, mostly mineralized. Irregular occurrence of water
			Jubaila	Aphanitic limestone	+118 M	Similar to Arab Formation above.
			Hanifa	Aphanitic limestone	113 M	
		Oxfordian	Tuwaiq	Aphanitic limestone	203 M	
		Callovian Bathonian Bajocian	Dhruma	Aphanitic limestone Sandstone South of 22° N and North of 26° N	375 M	Produces moderate amount of water north of 26° N and south of 22° N where it is generally represented by sandstone. South of 22° hydraulically connected with Minjur
		Toarcian	Marrat	Shale and aphanitic limestone	103 M	Yields little water of fair to poor quality
	Triassic	Upper	Minjur	Sandstone, Shale	315 M	Generally highly productive sandstone aquifer with flowing and non-flowing artesian conditions
		Middle	Jilh	Aphanitic limestone Sandstone and Shale	±326 M	Mostly hydraulically interconnected with Minjur, produces low quality water
		Lower	Sudair	Red 8, Green shale	116 M	
PALEOZOIC	Permian	Upper	Khuff, Faw	Limestone and Shale Sandstone South of 21° N	171 M	Moderately productive limestone aquifer, mostly mineralized water.
		Lower Undated	Wajed	Sandstone Precambrian Basement Complex	±950 M Calculated	Highly productive sandstone aquifer, with flowing and non-flowing artesian conditions
	Devonian	Lower	Jauf	Limestone, shale 8, sandstone	299 M	Productive generally in al Jouf area
	Ordovician & Silurian		Tabuk	Sandstone and shale	1072 M	Productive sandstone aquifer with flowing and non-flowing artesian conditions
	Cambrian		Saq (Umm Sahm, Ram, Quweira, Siq)	Sandstone	300-600	One of the most productive sandstone aquifer of Saudi Arabia, with flowing and non-flowing artesian conditions.

Source: After Otkum, Powers and Ramirez.

Table 21. Lithostratigraphic sequence in the Syrian Arab Republic

Era	Period		System	Average thickness (m)	Lithology
CENOZOIC	Quaternary		Recent	Variable	Alluvium, river deposits, marine marl
			Old	250	Conglomerate, marl, marine limestone
	Tertiary	Neogene	Contl.Pliocene	300	Conglomerate, sandstone, marine marl
			Marine Pliocene	200	Limestone, marl, sandstone
			(U.Fars)Contl. Miocene	200	shale, sandy shale, silt
			(L.Fars)Transitional Miocene	450	gypsum, anhydrite marl
			Marine Miocene	500	Argillaceous limestone, chalky marl, sandstone
		Neomilitic Paleogene	Oligocene	150	limestone, argillaceous limestone, sandstone
			Eocene	600	limestone, chalky limestone, chalky marl
			Paleocene	200	chalky marl, marl limestone, marl, chert
MESOZOIC	Cretaceous		U. Cretaceous	800	chalky marl, marl, marly limestone, chert
			M. Cretaceous	700	limestone dolomite, marly limestone
			L. Cretaceous	200	sandstone, limestone, shale
	Jurassic		U. Jurassic	300	marl, shale, limestone
			M. Jurassic	1600 ?	limestone, dolomite marl, anhydrite
			L. Jurassic	150	sandstone, limestone, anhydrite
	Triassic		Triassic	?	clastic blocks, ophiolites, radiolites

Source: C. Safadi, Outlook for Investment in Ground Water for Irrigation in the Syrian Arab Republic (1976).

Table 22. Syrian Arab Republic: ground-water regions

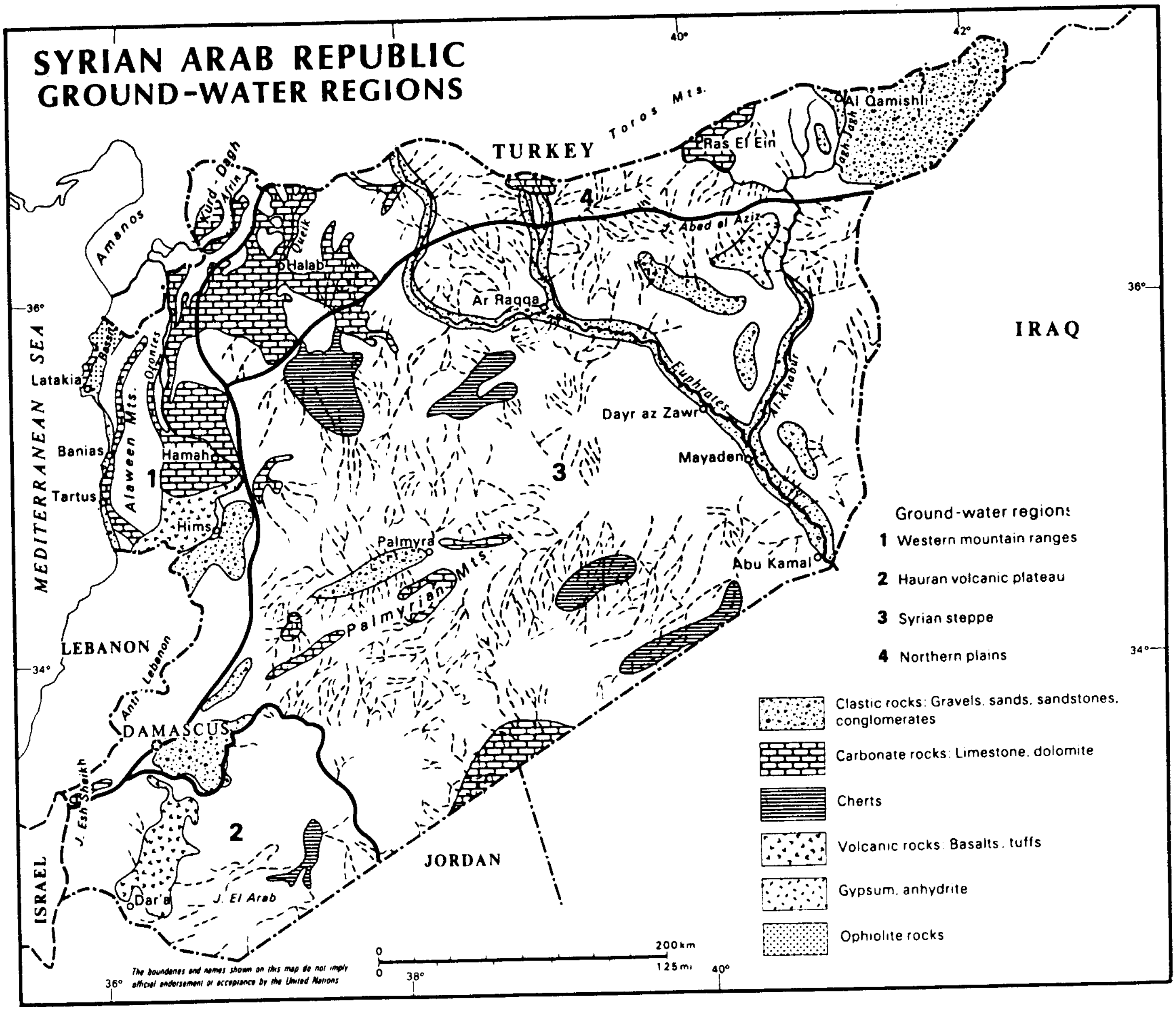
Ground-water region	Ground-water area	Recharge (mm^3/year)	Discharge (mm^3/year)	TDS (ppm)
Northern	Radd	350	65	500-1,000a/
Plain	Ras El-Ein	1,640	1,450	250-510
	Tel Abiad	...	...	250-510
	Halab	...	334	200-400b/
				1,000c/
Hauran volcanic plateau		314	-	155-500d/
Syrian Steppe	Damascus	501	518	
	Dawwa	...	...	
	Jabal Abdel Aziz	75	60c/	400-600
	Badiet Al-Jazira	15	...	
	Badiet Al-Sham	...	...	
Western mountain ranges	Ghab	...	88	
	Edleb	...	66	250-500
	Coastal	...	375	
	Offshore plains	...	...	
	Submarine springs	...	...	

Source: United Nations, Department of Technical Co-operation for Development, Ground Water in the Mediterranean and Western Asia. Natural Resources, Water Series No. 9, (New York 1982), pp. 153, 154, 156, 159 and 160. (United Nations publication, Sales No. E.82.II.A.8).

a/ 5,000 ppm to the south.
b/ Top aquifers.
c/ Deep aquifers.
d/ Local sharp increases in salinity could reach 2,300 ppm.
e/ 8,000 ppm in ground water below alluvium along the Euphrates.

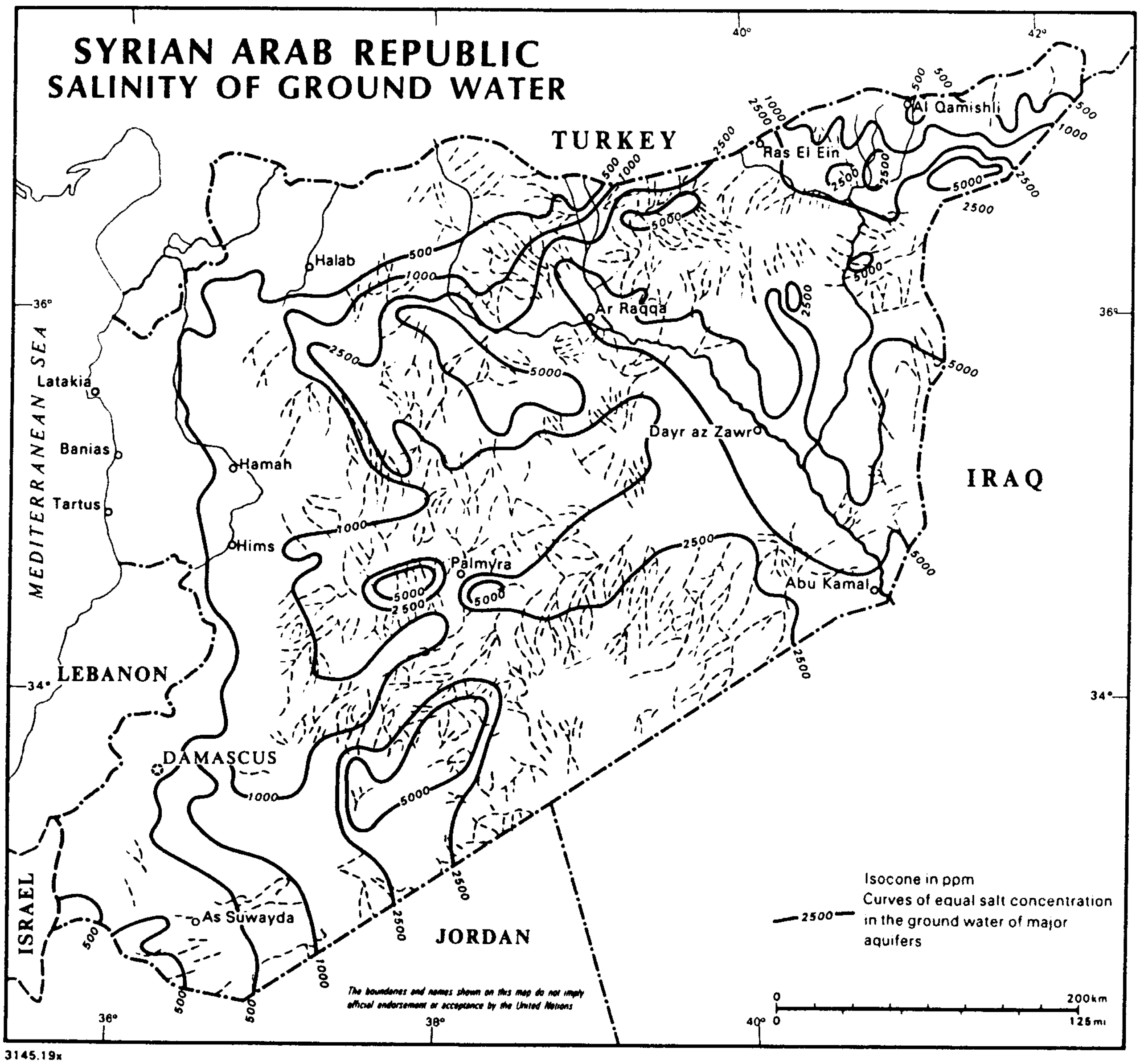
Note: ... Data not available.

Figure 22. Syrian Arab Republic: ground-water regions



Source: United Nations, Department of Technical Co-operation for Development, Ground Water in the Mediterranean and Western Asia, Natural Resources, Water Series No. 9, (New York 1982) p. 152 (United Nations publication, Sales No. E.82.II.A.8).

Figure 23. Syrian Arab Republic: salinity of ground water



Source: United Nations, Department of Technical Co-operation for Development, Ground Water in the Mediterranean and Western Asia, Natural Resources, Water Series No. 9 (New York 1982), p. 157 (United Nations publication, Sales No. E.82.II.A.8).

13. United Arab Emirates

The United Arab Emirates consists of Abu Dhabi, Dubai, Sharja, Ajman, Umm-al-Quwain, Ras El-Khaimah and Fujaira (see figure 24).

Geographically, it is bounded by the Gulf in the north and north-east, by Qatar and Saudi Arabia in the west, by the Gulf of Oman in the east, and by Oman and Saudi Arabia in the south. The climate is of the arid, tropical zone type. Thus, summers are hot and humid and winters are mild. Average annual rainfall is about 100 mm. Over half of this meagre quantity falls in December and January. Rainfall storms of short duration result in floods of varying magnitude. The average annual flood discharge ranges from 100,000 m^3 to 3 Mm^3. Four flood control and recharge dams are already in existence while another eight are proposed.

The United Arab Emirates obtains its fresh water supplies from two major sources: ground water and desalinated sea and brackish waters. Ground water provides 3 per cent of the Emirates potable water, and comprising of three main aquifer systems (see table 23). They are: (a) shallow alluvial, which underlies the central gravel plain and desert foreland. Its productive-zone thickness rarely exceeds 10m in the central plains. Aquifer water quality is good in the upper reaches of the main wadis, but it deteriorates eastwards towards the coast. The average annual recharge to the aquifer is 100 Mm^3. Over-withdrawal conditions are currently being encountered in the aquifer system; (b) The Batinah coastal plain aquifer: it is a narrow strip alluvium aquifer extending from the Musandous Peninsula to Omani forntier along the Batinah water quality is generally deteriorating; and (c) the deep carbonate aquifer; which is of poor quality; and no estimates are available for the aquifer recharge or its capacity.

Falajs and hand-dug wells are common in the United Arab Emirates. The annual ground water extraction is 120 Mm^3, but in 1985, this had reached 500 Mm^3/yr, which was distributed as follows (11):

- 100 Mm^3/yr, mostly brackish, which is used for drinking purposes after desalination or being blended with desalinated sea water;

- 400 Mm^3 for irrigation.

Ground-water resources in the United Arab Emirates come from the following well fields (12):

Emirate	No. of wells	Total production (gal/d)
Abu Dhabi	400	38,000,000
Dubai	57	6,000,000
Sharjah	180	12,000,000
Ras El-Khaimah	300	22,000,000
Umm Al-Quwain	95	3,500,000
Ajman	70	5,500,000
Fujaira	160	8,500,000

Figure 24. United Arab Emirates: hydrological zones

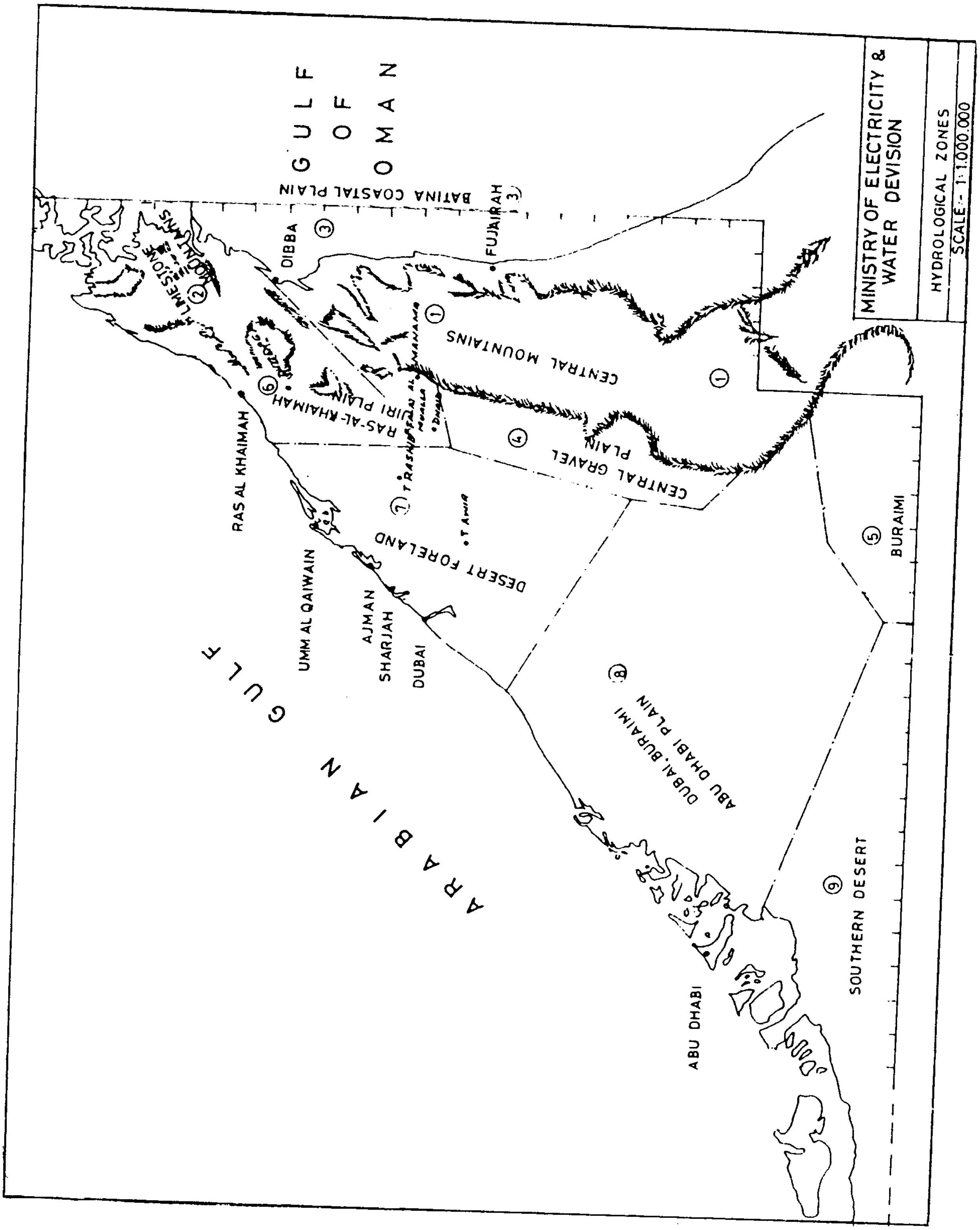


Table 23. United Arab Emirates: schematic stratigraphical- hydrogeological data

Zone / Formation	West coast W E	Desert W E	Djebel Faiyah Djebel Hafit	Gravel plain W E	Mountain W E	Batina coast W E
Quaternary	≲ 60m Sand,silt evaporites (gypsum, halite, anhydrite)	~60m 20 to 40 m Gravel, sand conglomerate mudstone Water quality, saline fresh	*	20-40m 0 m Gravel, sand conglomerate mudstone	Fill of valleys (gravel, sand)	Sand, gravel
Miocene-Oligocene	Marl, limestone dolomite, evaporites very	Marl, limestone dolomite evaporites saline	Marl, limestone dolomite evaporites artesian	Marl, limestone dolomite evaporites water	-	-
Eocene	?	≳ 250m arls, limestone water quality locally aline fresh ? High yield	Djebel Hafit 250m marls, limestone Yield Unknown	marls, limestone ground water?	-	-
Upper Cretaceous	? ?	(limestone) marl in general aquiclude	Djebel Hafit limestone marl, Djebel Faiyah limestone marl groundwater?	Marl, limestone caliche aquiclude on top, aquiclude below Semail b/ local ground water Hawasina+ local groundwater variable salinity	Maestricht limestone	Hawasina a/
Lower Cretaceous to Jurassic	Sand, marl, limestone, marl dolomite Ground water?	Sand, marl, limestone, marl dolomite Ground water?	Sand, marl, limestone, marl dolomite Ground water?	Sand, marl, limestone, marl, dolomite Ground water?	South and north of Dibba line Limestone locally: marls, dolomites, locally ground water	Like east coast
Triassic to Permian	Dolomite anhydrite boulder beds, marl, limestones Ground water?	Dolomite, anhydrite, boulder beds, marl, limestone Ground water?	Dolomite, anhydrite, boulder beds, marl, limestone Ground water?		North and south of Dibba line limestone, dolomite cretaceous on top water holding and water yielding	

Source: El Mohaylam Ismail, Water Resources. (United Arab Emirates, 1976).

a/ Hawasina formation: metamorphites, radiolarites, limestone, marl, shale, conglomerate, serpentinitic sills, volcanites.

b/ Semail formation: serpentinite, serpentinized ultrabasic rocks, Gabbro.

14. Yemen

The mean annual rainfall in Yemen is about 400 mm. Surface water is available as baseflow and springs. Ground water is the main source of water supply for domestic and agricultural purposes. Six major aquifers exist in Yemen, namely alluvium, recent volcanics, tertiary volcanics, sandstones, limestones and basement rocks (see table 24). Sea water intrusion results in the deterioration of coastal alluvium fresh water quality. Over-pumping in many of regions causes salinity to increase sharply to more than 1,000 ppm.

Mean annual flood flows are estimated at 1,750 Mm^3, and most are drained to the sea. Available ground water per year is estimated at 750 Mm^3, of which about 60 per cent exists in alluvial coastal strip, 17 per cent in the interior plains and 23 per cent in the eastern plain.

Annual water use in Yemen is estimated at 1,750 Mm^3, and is used for the following purposes:

- 275 Mm^3 for domestic purposes (15.7 per cent);
- 1,475 Mm^3 for irrigation (84.3 per cent).

Potable water is supplied from ground water, while 1,475 Mm^3 is used in agriculture (475 Mm^3 from ground water and 1,000 Mm^3 from surface water) (11).

Table 24. <u>Yemen: hydrogeological characteristics of rock units</u>

Formation	Age	Thickness (m)	Lithology	Hydrogeology
Tihama Plain Alluvials	Quaternary	0-600	Alluvium, conglomerate, silt sand and gravel. Thickens towards the coast	Good to excellent unconfined aquifer, good quality
Upper catchment alluvials	Quaternary	Variable up to 500	Alluvium, coarse boulders conglomerate to clay	Good to excellent unconfined aquifer, good quality
Quaternary volcanics	Quaternary	Variable	Basaltic lava interbedded with fluviatile and lacustrine sediments	Fair to good, unconfined
Yemen volcanics	Tertiary-Cretaceous	Variable up to 1,200	Laves, agglomerates, tuffs interbedded with alluvium	Fair to good, unconfined
Tawilah series	Cretaceous	± 400	Sandstone with conglomerates	Good, satisfactory water quality, unconfined
Amran series	Jurassic	? 350	Limestones, rocks, shales	Aquiclude or poor aquifer
Khalan series	Juraasic	100-500	Sandstone and conglomerates	Good semi-confined to confined but poor quality
Pre-Cambrian	Pre-Cambrian	?	Crystalline metamorphic and intrusive rocks	Aquifuge

<u>Source</u>: United Nations, Economic Commission for Western Asia, <u>Assessment of Water Resources Situation in the ECWA Region</u>. (Beirut, January 1981), (E/ECWA/NR/L/1/Rev.1), p. 239.

III. A REVIEW OF BRACKISH WATER DESALINATION IN THE ESCWA REGION

A. Background

Electrodialysis reversal (EDR) and reverse osmosis (RO) have proved to be the most applicable techniques for brackish water desalination in the ESCWA region, as well as world-wide. These techniques have revolutionized the process of water desalination in the last few years over a short span of time by improving technical and economic feasibility and its non-polluting and energy-saving characteristics relative to other systems. The increase in the number of reverse osmosis plants and production capacity has been remarkable, and is expected to continue. The growth of the reverse osmosis technology and its success is based on steady research and development in membrane science and the strategical exploitation of its parameters. The need to evolve an optimum system design in line with the latest available technology is obviously necessary. Design engineers are therefore required to keep a constant watch on developments in the field of membrane technology. Hence, the selection of a membrane for a particular process is made after a critical examination of its physical, chemical, biological and structural characteristics has been carried out. The use of desalinated brackish water depends primarily upon economic factors. Although the technology for brackish water desalination is available, economic considerations limit its use to special locations and to particular applications. As demand upon existing resources in areas suffering from water shortages becomes greater, water reuse could gain favour for certain uses, thus releasing natural water sources for more important purposes.

Therefore, a study of the source and location of brackish water, together with its quality, which usually govern the basic parameters of the desalination process, as well as the study of factors related to brackish raw water supply, will help to promote the procedure of membrane selection. Hence, raw water and the desired qualities of product water lead plant designers to decide on the extent of pre-treatment, membrane type, pressure-temperature parameters, the chemical additives required for conditioning the raw water, and the conversion ratio, etc.

Another important factor in brackish water desalination is the presence of total dissolved solids in the feed water, as this varies over time and place. Excessive pumping of brackish water over time reduces its quality, and affects the desalination process by requiring more pressure and, in turn, more energy, and this could necessitate a change in system design. Therefore, data collection regarding water quality is a very important consideration when a brackish water desalination plant is being designed. Table 8 provides a water quality analysis of different locations in the ESCWA region. Horizontial and vertical variations in total dissolved solids take place from one location to another in the same country, and from one country to another, depending on the hydrogeological characteristics of the aquifer that has been penetrated and on the location of water quality sampling. It is also important to fully evaluate the anions and cations that make up the feed water in order to avoid problems that might result from damage to the membranes during the ED and EDR process that could be caused by the presence of certain elements such as magnesium, calcium carbonate, etc.

B. Brackish water desalination in selected countries

The following section discusses brackish water desalination activities in selected countries that depend heavily on desalination as a main source of water supply, especially the Gulf countries, where conventional water resources are close to being depleted and the possibilities of renewal are very limited.

1. Bahrain

The water resources of Bahrain consist of brackish water (see tables 8 and 10).

The maximum tolerable level of TDS in drinking water from a health point of view is stipulated as being 1,500 mg/l, whereas Bahrain's ground water goes far beyond this level. From a quantitative and qualitative point of view, then future demand cannot be met from ground-water sources only. The alternative is to desalinate brackish and sea water by using reverse osmosis and MSF distillation, which was commenced in Sitra in 1975.

Future demand projections have been made on the assumption that per capita average supply in urban areas will be 320 litres/day, and 270 litres/day in rural areas. The ratio of peak demand to average annual daily demand is assumed to be 1.25. According to these assumptions, total water demand up to the year 2000 is as shown below (see figure 25).

Annual water demand in 10^6 cubic metres

Year	1985	1990	1995	2000
Demand	79.64	97.00	120.00	142.68
Distillate requirements (in Mgd)	40.00	50.00	64.00	78.00

A long-term policy of the development of Bahrain's water resources is the production of distilled sea water and its blending with brackish ground water in order to bring the chemical quality within acceptable drinking water standards. The capacity of Sitra dual (power/water) MSF was 5 Mm^3/yr (5 Mgd) when the plant began operating in 1975, in 1985, plant capacity was increased to 25 Mgd (34.9 Mm^3/yr). Simultaneously, in 1979, a reverse osmosis plant was also installed in the east to desalinate brackish water extracted from the Umm er Radhuma aquifer; it had a capacity of 14 Mm^3/yr (10 Mgd). Another reverse osmosis plant with a similar capacity is under construction at Ad Dur, and this is expected to begin operation early in 1988. (17), (18).

The following programme for the construction of desalination plants as planned by the Ministry of Electricity and Water, has been in operation since 1975.

Year	Water	Plant location	Desalination process	Production (Mgd)
1975	SW	Sitra (A)	Distillation	2.5
1975	SW	Sitra (B)	Distillation	2.5
1984	SW	Sitra 2	Distillation	5.0
1984	SW	Sitra 5	Distillation	5.0
1984	Br	Ras Abujarjur	Reverse osmosis	10.0
1985	SW	Sitra 3	Distillation	5.0
1985	SW	Sitra 4	Distillation	5.0
1986	SW	Al-Dur	Reverse osmosis	10.0
Total production				45.0

Source: Compiled from data supplied by Bahrain, Ministry of Electricity and Water.

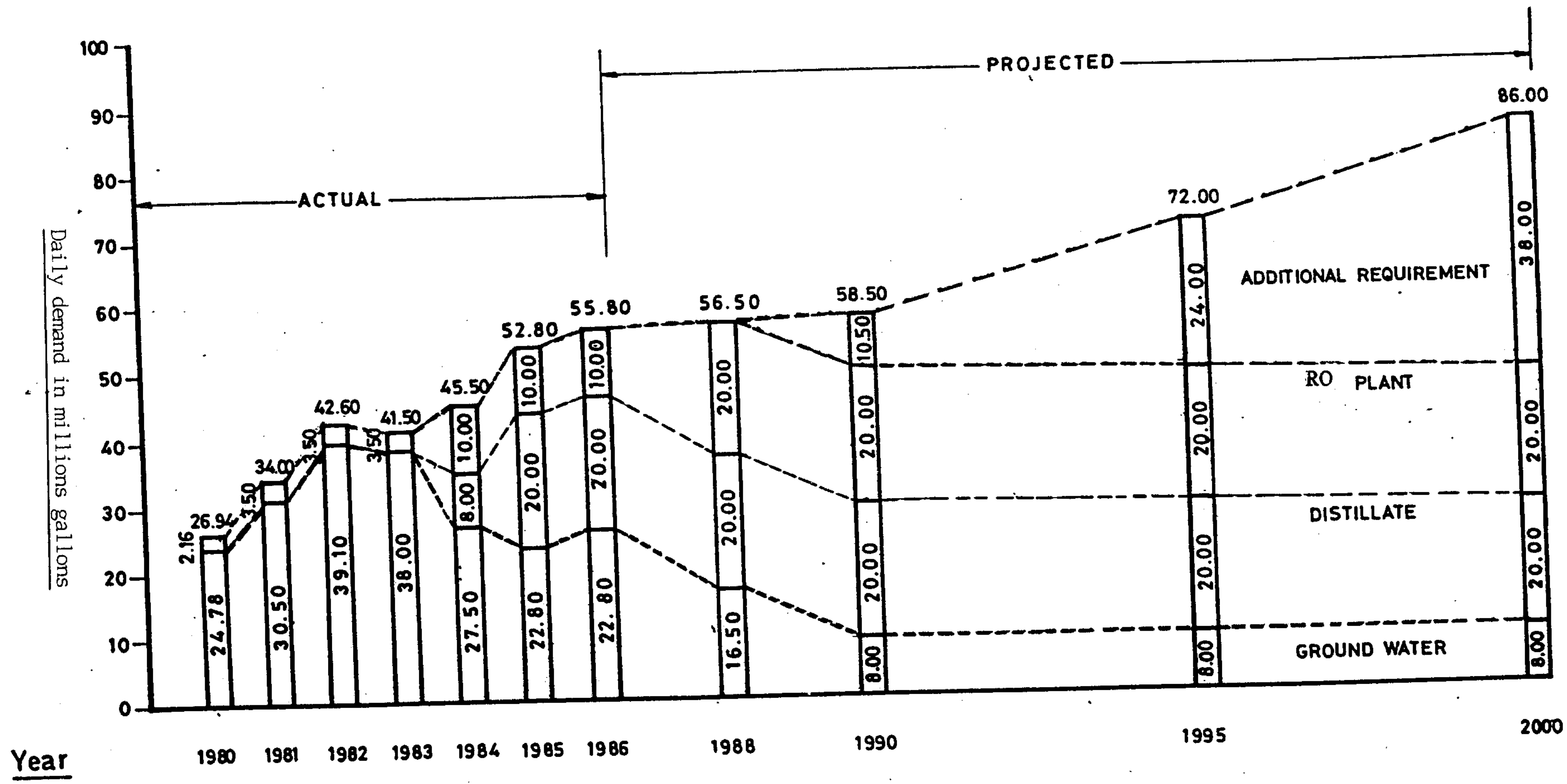
2. Kuwait

There has always been a great shortage of fresh natural water in Kuwait. Prior to 1925, people in Kuwait relied mainly on shallow wells that produced only limited supplies of drinking water. From 1925-1950, water supply was supplemented by the shipment of 80,000 to 90,000 gallons a day of potable water by dhow from Shatt Al-Arab in Basra, a distance of approximately 180 km. The journey took about 10 days, during which the dhows were subject to very bad weather conditions, including gales and dust storms. As a result, the quality of water was unreliable.

In 1950, Kuwait turned to the sea for fresh water, and a submerged-tube desalination plant produced 100,000 Gpd. Currently, one million cubic metres are produced daily from MSF desalination plants that are distributed as follows:

Shueikh	32 Mgd
Shuaiba north	14 Mgd
Shuaiba south	30 Mgd
Doha east	43 Mgd
Doha west	96 Mgd

Figure 25. Supply and resources demand in Bahrain, 1981-2000



Source: Data supplied by Bahrain, Ministry of Electricity and Water, 1986.

About 8 to 10 per cent of brackish water is added to distillate water in order to meet World Health Organization (WHO) standards for potable water, i.e. 500 to 800 ppm.

Fresh ground water from the Rawdatain and Umm Al-Aish well fields (TDS 500 to 1500 ppm), are utilized as drinking water following chlorination. The fresh water potential is about 6,000 m^3/day from both fields, but current daily pumping is 680 m^3/day, and the remainder is kept as fresh water strategic reserves.

Brackish ground water from the Sulaibiya and Shagaya fields (2,500-7,000 ppm) is put to different uses such as blending with distilled water, garden irrigation and limited industrial use. Brackish water extraction in 1984 reached 195,000 m^3/day. Figure 26 indicates the rate of production of desalinated, fresh and brackish waters between 1954 and 1984, while figure 27 indicates the rate of production of brackish water within the same period.

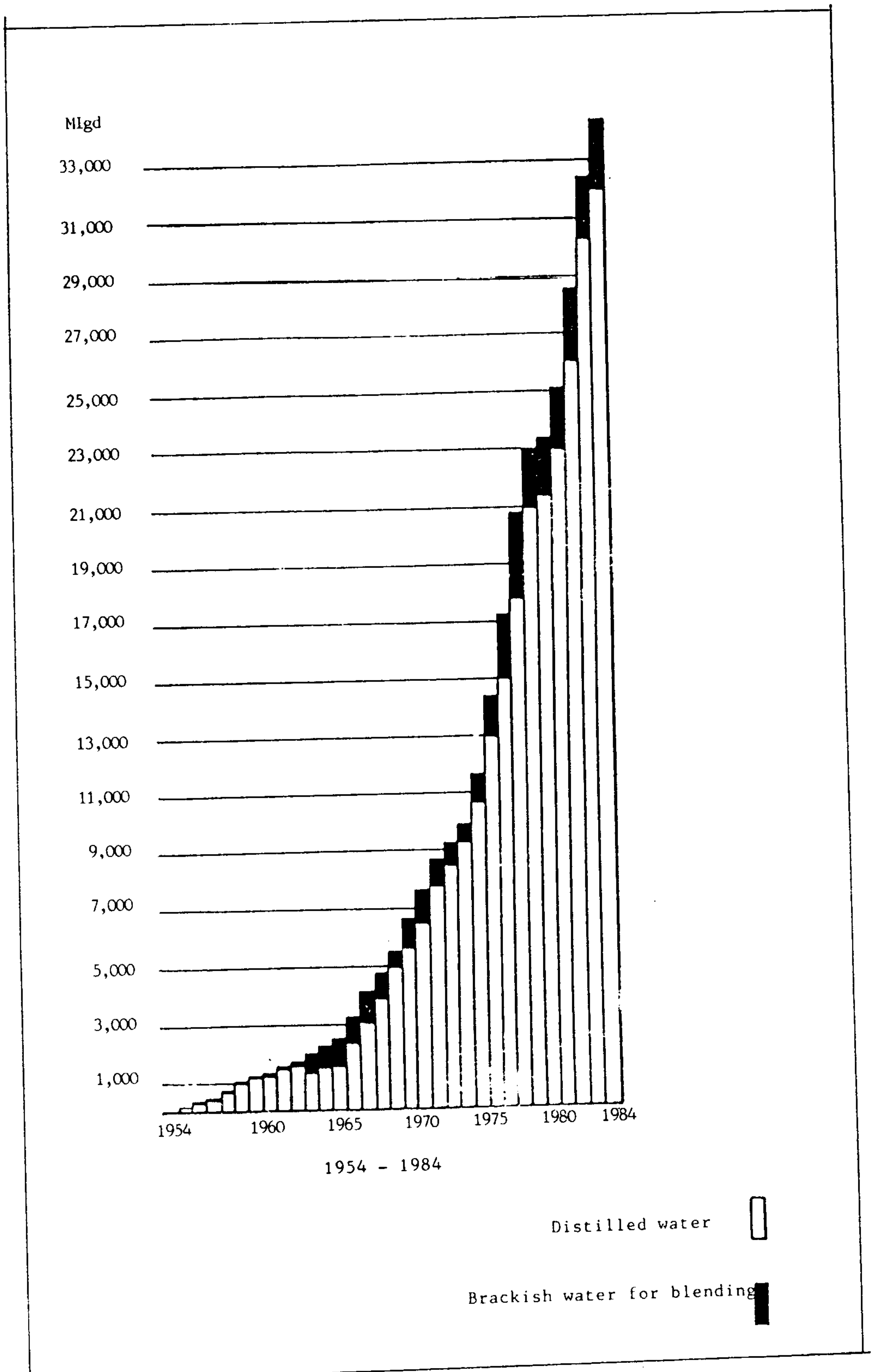
The only governmental brackish water desalination plant reported officially is Shagaya Military Camp using electrodialysis reversal, which consist of two units with a maximum daily capacity of 113.6 m^3/day per unit. Reverse osmosis plants of small capacities are in existence, but no official records of their numbers or source and quantity of feed water used are available, (9), (19).

3. Qatar

Until 1953, Qater depended mainly on ground water to meet its domestic and agricultural needs. Hand-dug wells were in common use in some areas. As demand increased, the desalination of sea water was resorted to, first in the capital Doha (85 per cent of Qatar's population lives in Doha and Umm Said), where a desalination plant was built (680 m^3/day). Desalinated capacity subsequently increased to 264,000 m^3/day (96 Mm^3/year) in 1986. The first distillation plant with a capacity of 0.094 Mm^3/yr, was completed in 1954, which was blended with an equivalent amount of brackish water. In 1985, a new plant was constructed, and total output was raised to 0.713 Mm^3/yr. In 1963, the first two MSF units with a capacity of 2.489 Mm^3/yr were constructed at Ras Abu Aboud. In 1977, the Ras Abu Fantas plant was commissioned, bringing the total production of distillate to 4.435 Mm^3/yr. Water production from different sources in the period 1960-1981 is illustrated in figure 28, published by the water Department, Ministry of Electricity and Water in the Statistical Report 1971-1981.(20).

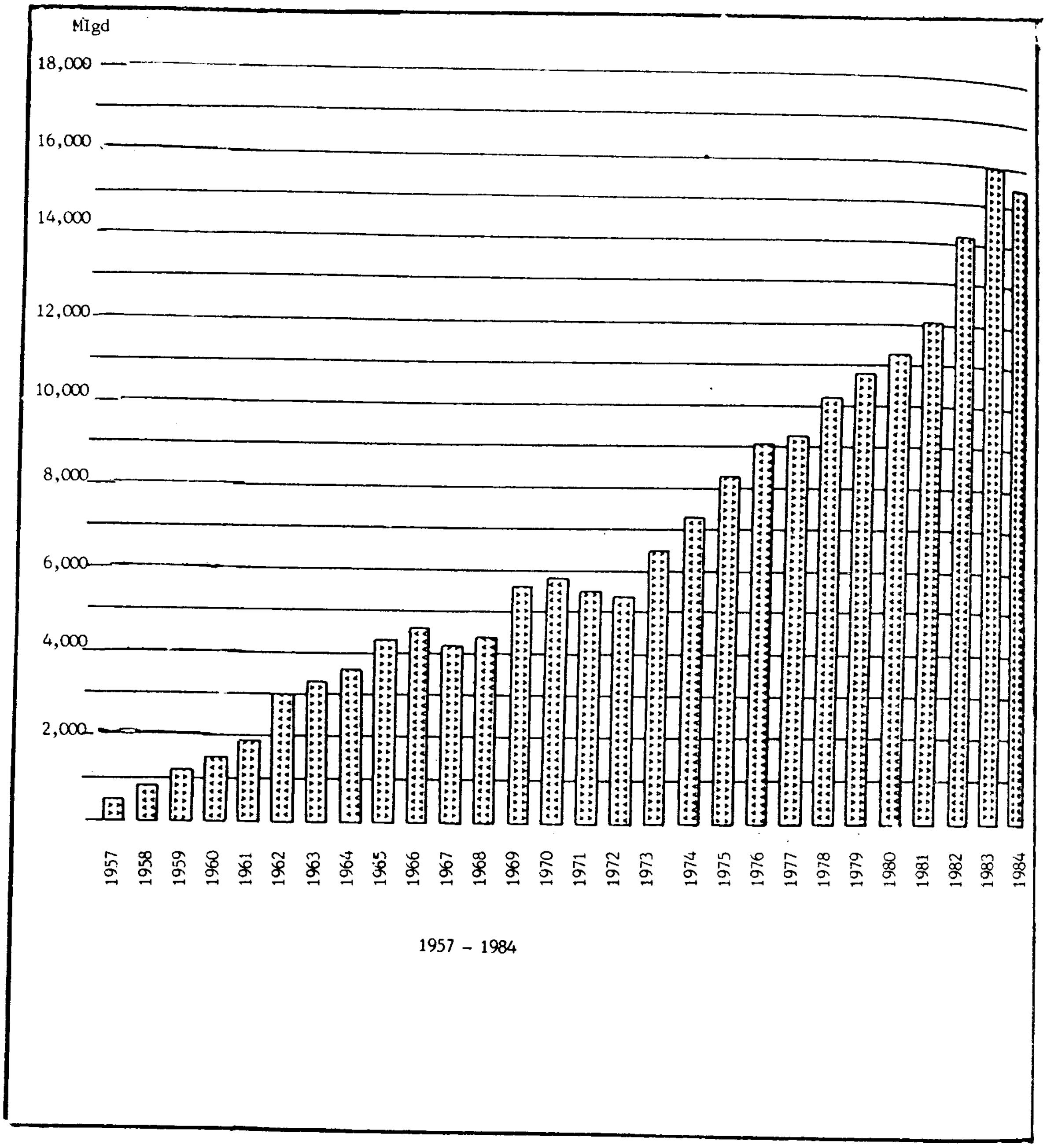
Ground water resources in Qatar are used for domestic and agricultural purposes. The estimated quantity of current ground water abstraction from all aquifers for agricultural purposes is more than 100 Mm^3/yr. Renewable water (recharge) is estimated at 28 Mm^3/annum. No further development of ground water appears possible at present because of the current over-extraction of ground-water reserves, which causes an upward movement of brackish ground water and lateral sea water intrusion. It is expected that the quality of potable water will exceed usable limits by the year 2000.

Figure 26. Distilled and fresh water production in Kuwait, 1954-1984



Source: Data supplied by Kuwait, Ministry of Electricity and Water.

Figure 27. Brackish water productin in Kuwait, 1954-1984



Source: Kuwait, Ministry of Electricity and Water.

4. Oman

The amount of surface water is estimated at some 160 Mm^3/year. plans exist for the construction of storage and recharge dams. Ground water resources in Oman are limited. Batinah coastal ground water is becoming brackish owing to the excessive pumping, which results in sea water intrusion.

Water utilization for different purposes increased very rapidly in the 1970s, making it necessary to develop non-conventional water resources. In 1976, the Al-Ghabra desalination and power plant was erected in the area of the capital to produce between 4.8 to 7.2 Mgd depending on the chemicals used. The MSF plant currently in operation provides potable water, which is then blended with brackish water and supplied to the area of the capital. Salala domestic water supply increased from 5.2 Mm^3/year in 1982 to 5.5 Mm^3/year in 1984, and demand projections indicate that water use could reach 10 Mm^3 in 1990.

In 1982, a second desalination unit with a capacity equal to the first one went into operation. At full capacity, the two units are expected to produce up to 12 Mgd. That is sufficient to supply the capital with most of its needs; for the remainder, it has to rely on well fields at Seeb and Wadi Adai.

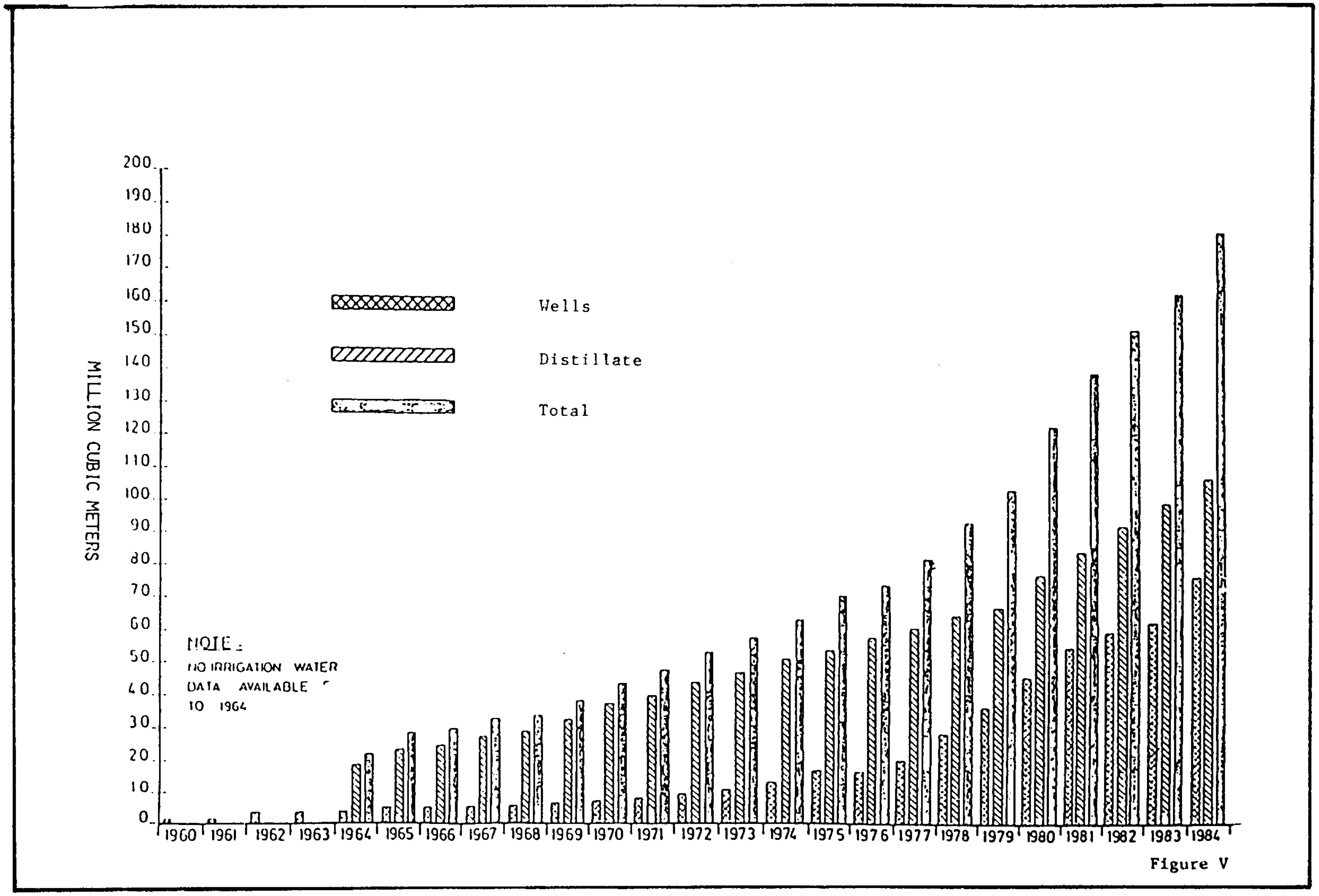
In certain areas where potable water is not available, especially in coastal areas like Ras Al-Had, Al-Dukum, and Ras Madraka, the Ministry of Electricity and Water has initiated projects for the supply of water to consumers through the establishment of small-scale sea water desalination plants.

Brackish water resources are used for agriculture or are blended with distillate water. Two small brackish water reverse osmosis desalination plants have been reported in Oman, each with a capacity of 0.002 m^3/d (15)(16).

5. Saudi Arabia

Fresh water resources in Saudi Arabia are limited. The existing sources of water in different regions can be grouped into the following types of resources: renewable, non-renewable, desalination and effluent reuse. Most of the known renewable water resources in Saudi Arabia involve surface run-off and the pumping of water from shallow recharged aquifers and springs. The estimated volume of these resources is about 1,145 Mm^3/year, which constitutes about 25 per cent of the total. They are mainly concentrated in the south-western region, where they are used to supplement other sources needed to meet the growing urban, industrial and agricultural demand. A good quantity of non-renewable water exists in deep aquifers in the central and eastern regions. Over-pumping of ground water in the coastal regions has created salt water intrusion problems. Moreover, the quality of ground water sources deteriorated rapidly, and has become increasingly saline. Most of the wells in the country are either brackish or are turning brackish. Because of the limited conventional supplies available, Saudi Arabia came to rely heavily upon desalinated water. It had the largest potential for desalination, and had a total capacity of 2.5 Mm^3/d in 1983. The national water balance is shown in table 25, which indicates that desalination is an essential source of water in Saudi Arabia.

Figure 28. <u>Annual rate of potable water produced in Qatar between 1960 and 1985</u>
(cubic metres)



Source: Data supplied by Qatar, Ministry of Electricity and Water, Water Department.

Table 25. Saudi Arabia: national water balance

(Millions of cubic metres per year)

Region	Water resources	A.H. 1400	A.H. 1405	A.H. 1410	A.H. 1420	Water utilization	A.H. 1400	A.H. 1405	A.H. 1410	A.H. 1420
Central	Non-renewable	2,000	2,000	2,000	2,000	Urban and industrial	128	196	298	579
	Renewable	200	200	200	200	Rural and livestock watering	8	8	9	11
	Desalination	-	193	193	193	Irrigated agriculture	890	790	1,090	1,710
	Reclaimed from urban waste water	-	40	90	200	Surplus (deficit)	1,174	1,439	1,086	293
	Sub total	2,200	2,433	2,483	2,593	Sub total	2,200	2,433	2,483	2,593
Western	Non-renewable	-	-	-	-	Urban and industrial	219	343	479	897
	Renewable	225	225	225	225	Rural and livestock watering	7	7	7	8
	Desalination	52	237	392	777	Irrigated agriculture	125	200	255	405
	Reclaimed from urban waste water	-	85	155	330	Surplus (deficit)	(74)	(38)	31	22
	Sub total	277	547	772	1,332	Sub total	277	547	772	1,332
Eastern	Non-renewable	1,000	1,000	1,000	1,000	Urban and industrial	68	153	231	402
	Renewable	-	-	-	-	Rural and livestock watering	1	1	1	1
	Desalination	11	169	169	169	Irrigated agriculture	367	470	550	575
	Reclaimed from urban waste water	-	15	25	50	Surplus (deficit)	575	560	412	241
	Sub total	1,011	1,184	1,194	1,219	Sub total	1,011	1,184	1,194	1,219

Table 25 (continued)

Region	Water resources	A.H. 1400	A.H. 1405	A.H. 1410	A.H. 1420	Water utilization	A.H. 1400	A.H. 1405	A.H. 1410	A.H. 1420
Northern	Non-renewable	450	450	450	450	Urban and industrial	20	32	54	111
	Renewable	15	15	15	15	Rural and livestock watering	6	7	9	12
	Desalination	-	4	4	4	Irrigated agriculture	150	138	180	220
	Reclaimed from urban waste water	-	-	15	40	Surplus (deficit)	289	292	241	166
	Sub total	465	469	484	509	Sub total	465	469	484	509
South-western	Non-renewable	-	-	-	-	Urban and industrial	67	99	149	290
	Renewable	705	705	705	705	Rural and livestock watering	5	5	5	6
	Desalination	-	2	36	55	Irrigated agriculture	300	275	270	310
	Reclaimed from urban waste water	-	-	50	110	Surplus (deficit)	333	328	367	264
	Sub total	705	707	791	870	Sub total	705	707	791	870
Kingdom	Non-renewable	3,450	3,450	3,450	3,450	Urban and industrial	502	823	1,211	2,279
	Renewable	1,145	1,145	1,145	1,145	Rural and livestock watering	27	28	31	38
	Desalination	63	605	794	1,198	Irrigated agriculture	1,832	1,873	2,345	3,220
	Reclaimed from urban waste water	-	140	335	730	Surplus (deficit)	2,247	2,616	2,137	986
	TOTAL RESOURCES	4,658	5,340	5,724	6,523	TOTAL UTILIZATION	4,658	5,340	5,724	6,523

Source: Saudi Arabia, Ministry of Planning, Third Development Plan 1980-1985.

Table 26. Selected desalination plants in Saudi Arabia

Location	Approximate year operations began	Water production (1000m^3/day)	Capacity power MW	Process	Constract cost (Million of SRls)	Unit cost SRls/m^3
Wajh I	1969	0.227	-	MSF	1.96	1.53
Jeddah I	1970	18.925	50	MSF	179.32	1.69
Khobar I	1973	28.388	-	MSF	162.45	0.92
Khafji I	1974	0.454	-	MSF	10.39	4.08
Jeddah II	1978	37.850	80	MSF	720.30	3.40
Jeddah III	1979	75.700	200	MSF	180.00	4.24
Jeddah IV	1982	189.250	500	MSF	2,586.00	2.44
Yanbu/						
Madina I	1981	94.625	250	MSF	1,372.00	2.59
Jubail I	1982	113.550	350	MSF	2,298.00	3.61
Khobar II	1982	189.250	500	MSF	3,077.00	2.90
Jubail II	1984	946.250	1,300	MSF	5,419.00	1.02
Jeddah	1979	12.112	-	RO a/	103.20	0.83
Yanbu	1981	4.996	-	RO a/	42.30	0.83
Jubail	1980	15.140	-	RO b/	9.63	0.11
Berri	1979	6.813	-	RO b/	4.13	0.11
Riyadh	1979	4.542	-	RO b/	3.44	0.12
Majna	1978	3.758	-	RO b/	2.75	0.12

Source: Compiled from data supplied by the Saline Water Conversion Corporation.

a/ Reverse osmosis by sea water.
b/ Reverse osmosis by brackish water.

Note: $US 1 = 3.44 Saudi Arabian riyals (SRls).

Desalination is an alternative source that has been utilized extensively in Saudi Arabia, and it is considered to be one of the most important engineering tasks that faces Saudi Arabia today. Since the creation of the Saline Water Conversion Corporation (SWCC) in 1965, several desalination plants have been established on the coast by the Red Sea and the Gulf. As a matter of fact, Saudi Arabia is considered the first in production of desalinated water. In 1984, the total rate of desalination of brackish and sea water reached 930 Mm^3/day. SWCC commissioned the largest MSF facility in the world, with a capacity of about 1.1 Mm^3/d. The water produced will be pumped inland over 485 km to the capital, Riyadh. Table 26 gives details of selected desalination plants in Saudi Arabia, (2), (18).

6. United Arab Emirates

In addition to the ground water that is exploited, sea and brackish water desalination is considered to be a major water supply component that provides most of the potable water. The distribution of distillation in the available desalination plants in the United Arab Emirates is given in table 27.

Table 27. Distribution of desalination plants in the United Arab Emirates

Station	Emirate	Full capacity (Mgd)	Date operations began
Abu Dhabi	Abu Dhabi	6 x 2 = 12	1974 (SW)
Abu Dhabi Steam	Abu Dhabi	4 x 3 = 12	1977 (SW)
East Umm En Nar	Abu Dhabi	3 x 5 = 15	1979 (SW)
West Umm En Nar	Abu Dhabi	4 x 5 = 20	1984 (SW)
East Umm En Nar	Abu Dhabi	2 x 5 = 10	1984 (SW)
Ruwais (steam)	Abu Dhabi	2 x 2.9 = 5.8	1984
Jabal Ali Power	Dubai	5 x 2.9 = 14.5	1986 (SW)
Dubai Power	Dubai	5 x 5 = 25	1980 (SW)
Dubai Steam	Dubai	3 x 5.7 = 17.2	1984 (SW)
Dubai Power	Dubai	6 x 5.2 = 30.2	(SW) a/
Layyain Power	Sharjah	2 x 4.5 = 9	1982 (SW)
Layyah Power	Sharjah	2 x 4.5 = 9	1983 (SW)
RO plant Buraitat	Ras Al Khaima	3 x 0.5 = 1.5	1976 (Br)
UAQ brackish RO plant	Umm Al Quwain	4 x 0.5 = 2	1986 (Br)

Source: Compiled from data supplied by the United Arab Emirates, Ministry of Electricity and Water.

a/ Under construction.

Recently a 2.0 Mgd brackish water desalination plant was commissioned in Umm Al Quwain. The plant is designed to treat brackish water with 4,500 ppm TDS. It could be upgraded to treat brackish water of 20,000 ppm.

The major water supply systems in operation in each of the Emirates is as follows (21):

(a) Abu Dhabi

Six desalination plants provide the city with 9,000 m^3/day of water, in addition to 7,800 m^3/day that is carried to Abu Dhabi from the Al Ain fresh water sources. Al Ain deals with fresh ground water at the rate of 15,014 m^3/day.

(b) Dubai

Dubai is supplied mainly with desalinated sea water at the rate of 40 Mgd, in addition to 15 Mgd that is pumped from fresh ground water sources.

(c) Sharjah

Sharjah potable water is produced from 9 Mgd of desalinated sea water, in addition to 10 M which is extracted from ground water in the Al Baidryet and Hamdah regions.

(d) Ajman

A central desalination plant situated on the west coast will provide Ajamn and the other Emirates with 8 Mgd. In addition, 2.5 Mgd is extracted from ground water sources at Tawa Rashid and Ruq'at ak-Shanuf.

(e) Um Al Quain

A water well field of 1.5 Mgd at Mealla and Furaij provides the Emirate with potable water, in addition to water which comes from the central desalination plant on the west coast.

(f) Al Fujairah and the east coast

A central desalination plant of 4 Mgd was installed on the east coast to cover the needs of Al Fujaira and cities situated on the east coast.

IV. ENERGY REQUIREMENTS

A. General

The establishment of an efficient brackish water desalination project depends on many factors, of which the following are the more significant:

- Dependable supplies of brackish water;
- Availability of energy;
- Brine disposal access;
- Availability of capital;
- Availability of management and control;
- Availability of skilled labour;
- Availability of maintenance facilities.

Among the above factors, energy is of special significance. From a cost point of view, energy is necessarily a limiting factor, but other factors such as labour, capital and maintenance requirements could be of equal or even greater importance. Energy accounts for between 15 and 40 per cent of total annual costs in most of the established desalination plants, while it accounts for between 15 and 85 per cent of the daily operation and maintenance costs of the water produced. Energy costs increase in proportion to the size of the plant. However, many factors contribute to the calculation of energy costs, among which are the energy source, temperature and salinity levels of the raw and produced water, as well as site location. Therefore, considerable effort is being made to reduce the equivalent energy consumption per cubic metre of fresh water produced in desalination plants. Current energy consumption for the different processes is shown in table 28. The types of energy used in the desalination processes are illustrated in table 29, (3).

The type of energy available at the plant is one of the factors that can influence the selection of a desalination processes. Some of the processes operate on the basis of a specific form of energy, is as illustrated in table 28, which indicates that RO, ED and EDR rank lowest in the energy consumption required to produce fresh water. At present, most of the plants operating in the ESCWA region are powered directly by conventional fossil fuels, or by electrical energy, while a few experimental systems are powered by renewable energy.

B. Energy requirements for desalination

Desalination processes require some form of energy to operate them. They involve a change in phase as distillation includes a high rate of energy circulation. The energy needed to operate the system will be only a fraction of the latent heat of the solvent, and will be independent of the amount of solution present. The energy required in membrane desalination processes, on the other hand, depends upon the selection of transport such as ED and EDR,

Table 28. Energy consumption for the different desalination processes

Desalination process	Energy consumption: Thermal kcal/m^3		Energy consumption: Electrical kWh/m^3	Total Energy: kcal/km^3 a/	Total Energy: Kg of fuel/m^3
RO plants					
Brackish water b/	0	+	3	7,500	0.75
Sea water	0	+	12	30,000	3.00
Electrodialysis					
Brackish water	0	+	3	7,500	0.75
Sea water	–		10–45		
Distillation process					
MSF					
Flash ratio = 8	70,000	+	3	77,500	7.75
Flash ratio = 14	40,000	+	5	25,500	5.25
Multiple effect	550,000	+	0	55,000	55.00
Vapour compresssion	0	+	16	40,000	4.00
Solar distillation	–	+	1,250 (approx.)		

Source: Symposium on Water Resources in Saudi Arabia, 17-20 April 1983, King Saud University, Management Treatment and Utilization, vol. 3, Desalination, (College of Engineering)

a/ Hypothesis 1 kWh = 2,500 kcal (R = 35 per cent).

b/ Brackish water salinity level ranges between 2,000 to 3,000 ppm.

Table 29. Types of energy used in desalination processes

Process	Energy type	
	Heat	Mechanical
Distillation: MSF, ME	70° C-120° C	-
Vapour compression	Steam ejector	Electric motor, internal combustion engineer turbine
Freezing	Absorption cooling cycle	Vapour compression cooling; motor, engine or turbine-driven vapour compresser
Reverse osmosis		Electric motor, engine, or turbine driven high pressure pump
Electrodialysis		DC electrical current

Source: Symposium on Water Resources in Saudi Arabia, 17-20 April 1983, King Saud University, Management Treatment and Utilization, vol. 3, Desalination, (College of Engineering).

which in turn depend on the salinity of the feed water and the product obtained. Spiegler's formula (1966) for the calculation of theoretical energy requirements, U, at various levels of salinity of feed, product and blow-down, based on thermodynamic relations is as follows:

$$U = 5.21\ (N_f - N_p)\left(\frac{\ln b}{B-1} - \frac{\ln a}{a-1}\right) \text{kWh/kgal}$$

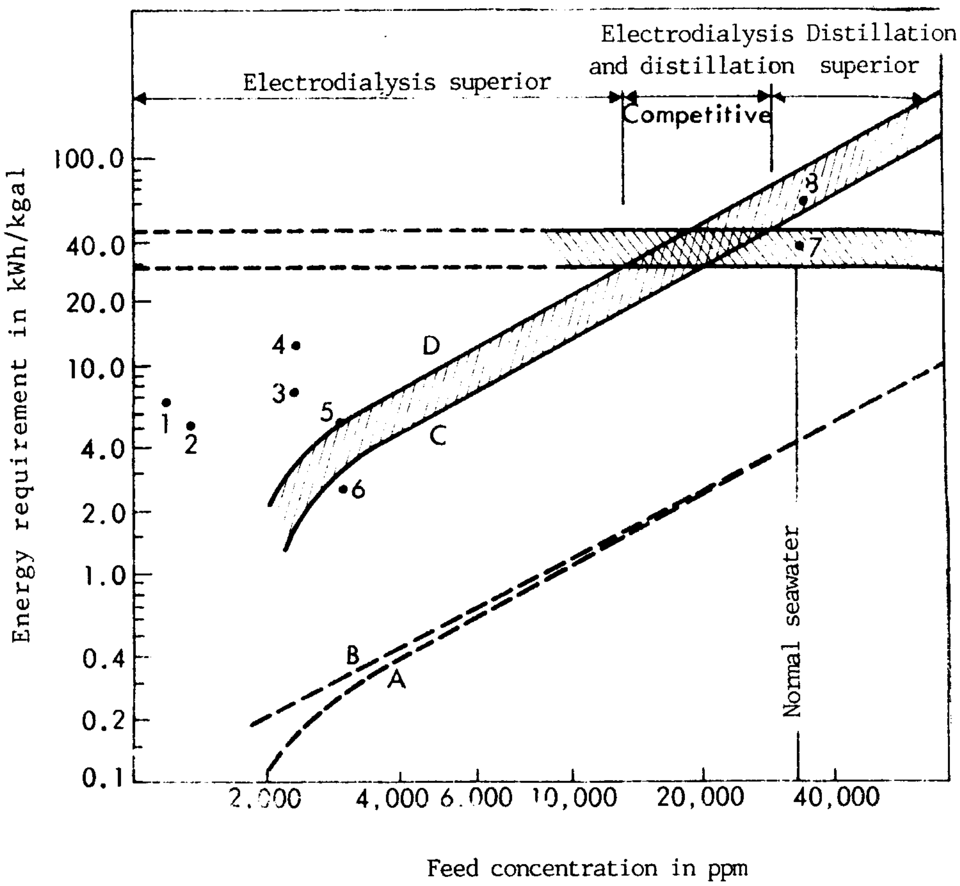
where the items N_f, N_c and N_p represent concentration in equivalents per litre of feed, concentrate and product, respectively. In actual systems, more energy is required to maintain the large driving forces necessary to obtain practical production rates. In most reverse osmosis and ED systems, the energy required to achieve practical production rates may be 10 to 20 times higher. Shuffer and Mintz have given the theoretical and actual energy requirements as a function of the salinity of the feed water for EDR, and compared them with distillation, as can be seen in figure 29. It is clear that EDR requires less energy than distillation for salinity levels of up to 11,000 ppm, which is beyond the limit of brackish water.

As an illustration, the data on power consumption for some existing ED and EDR plants are given in table 30, which shows the effects of some of the parameters such as feed water TDS and plant capacity on power consumption.

The energy costs involved in most desalination processes account for 45 to 85 per cent of the daily maintenance and operation costs of the product, and from 15 to 40 per cent of total annual costs. As plants increase in size, the percentage of costs expended on energy also increases. Although the energy utilized by a particular process for the production of a given quantity of water can be estimated quite accurately, the cost of energy varies widely among processes and locations, according to the energy source, temperature levels and previous use. Electricity costs thus have to be ascertained on a site-specific basis. The actual cost of electricity in the ESCWA region could reach $0.3/kWh. Moreover, a careful estimate is needed in order to calculate energy for a given plant, as this is the most significant variable cost in the production of desalinated water. Reed (1981) has estimated the cost of energy relative to the total plant cost for brackish water, as follows:

	Percentage of O and M Plant size (m^3/d)				Percentage of total annual costs Plant size (m^3/d)			
Description	3,800	19,000	38,000	190,000	3,800	19,000	38,000	190,000
Process								
RO	44	56	59	62	26	33	35	38
EDR 1	48	60	65	-	20	24	26	-
EDR 2	61	70	74	-	29	34	36	-

Figure 29. Energy requirements for the distillation and electrodialysis of salt water



Legend:

A Theoretical energy for electrodialysis and reverse osmosis.
B Theoretical energy for distillation.
C Estimated actual energy for electrodialysis.
D Estimated actual energy for distillation.

Source: B.H. Khoshaim and J.S. Williamson, eds., Solar Wind Desalination, Proceeding of the Second SOLERAS Workshop, Denver, Colorado, USA, March 1981, p. 102.

Note: Average equivalent weight of salt = 60 blowdown concentration; distillation to produce pure water; and electrodialysis to produce 0.005 - N(300 ppm) product. Plotted point show actual energy consumption for some ED plants; numbers refer to plant data as presented in table 1.

Table 30. Technical data for selected plants

Location[a]	Concentration (ppm) Feed	Concentration (ppm) Product	Process	Concentration ratios feed/product (Percentage)	Capacity kgal/d	Power consumption kWh/kgal
1	845	190	RO	4.45	500.0	6.9
2	1,400	500	EDR	2.80	4,000.0	5.1
3	2,358	573	RO	4.10	2,100.0	7.5
4	2,400	500	RO	4.40	500.0	13.6
5	3,000	550	EDR	4.45	170.0	5.0
6	3,000	500	RO	6.00	516.0	2.7
7	35,000	500	ED	70.00	98.0	32.9
8	35,000	500	RO	70.00	38.7	61.3

Source: B.H. Khoshaim and J.S. Williamson, eds., Solar Water Desalination, Proceedings of the Second SOLERAS Workshop, Denver, Colorado, USA, March 1981, p. 103.

a/ The ED, EDR plants from different locations, both within and outside ESCWA region, are the same as those referred to in figure 8.

C. Desalination using renewable energy sources

In both urban and rural areas, considerable attention has been directed towards the use of renewable energy sources in desalination, because of the high costs of storage, of obtaining standard fuel, and the lack of power sources in rural areas. Renewable energy, in the form of solar and wind power, requires no further investment once the proper energy collection system has been installed. Efforts are being made in many ESCWA countries (e.g. in Egypt and Jordan) to explore the possible applications of alternative energy sources to desalination processes, though on a small scale because of the high initial capital costs involved. Renewable energy sources are likely to begin to compete with conventional sources in small-scale applications in rural areas. The basic criteria that should be considered in connection with the sources of renewable energy that are appropriate for desalination include the following:

- The energy form must be freely available to the desalination plant operator;
- The energy form must be available at the time when desalination is required;

- The energy conversion that transforms the renewable energy source applied to a particular desalination process must be easily managed and controlled by the desalination operators;

- The renewable energy conversion technology must be mature enough to ensure the reliable operation of the desalination plant in the field.

All sources of renewable energy exist in the ESCWA region. However, it should be noted that the most widespread source in different parts of the world is solar energy. It is primarily available in the form of low-grade energy. Most efforts at solar desalination have been aimed at transforming this energy directly into heat, especially for distillation processes. More recently, solar energy has been converted into electricity (the solar photovoltaic effect), or mechanical power (by solar thermal pumps), which can be used in the reverse osmosis and electrodialysis processes.

Other forms of energy such as a biomass energy, which can also be converted into heat or transformed into mechanical shaft power, are still being developed. Wind energy is used mainly in the form of mechanical shaft power, which can be used directly or converted into electricity or heat, depending on the specific desalination project (1).

Each of these energy forms is discussed briefly below, with emphasis being placed on solar and wind energy, especially with regard to the situation in the ESCWA region.

1. <u>Solar energy</u>

The use of solar energy for desalination has generated more interest than all other known renewable energy sources. Solar distillation has been experimented with over the last four centuries. Apart from basic solar stills, the development of renewable energy sources for desalination is still in its infancy. Commercial development and large-scale applications can be expected to take some time to implement.

Solar energy varies during the day and from day to day, and depends on location and atmospheric conditions. Hence, its applications must provide for the variation in supply or should ensure some type of storage in order to offset these variations and to deliver power for longer periods than actual sunlight duration.

Energy converters are used to convert solar energy directly into heat or electricity, or other forms of energy. The heat converters commercially available are flat plate collectors, focusing collectors and solar ponds, which are mainly used for distillation desalination.

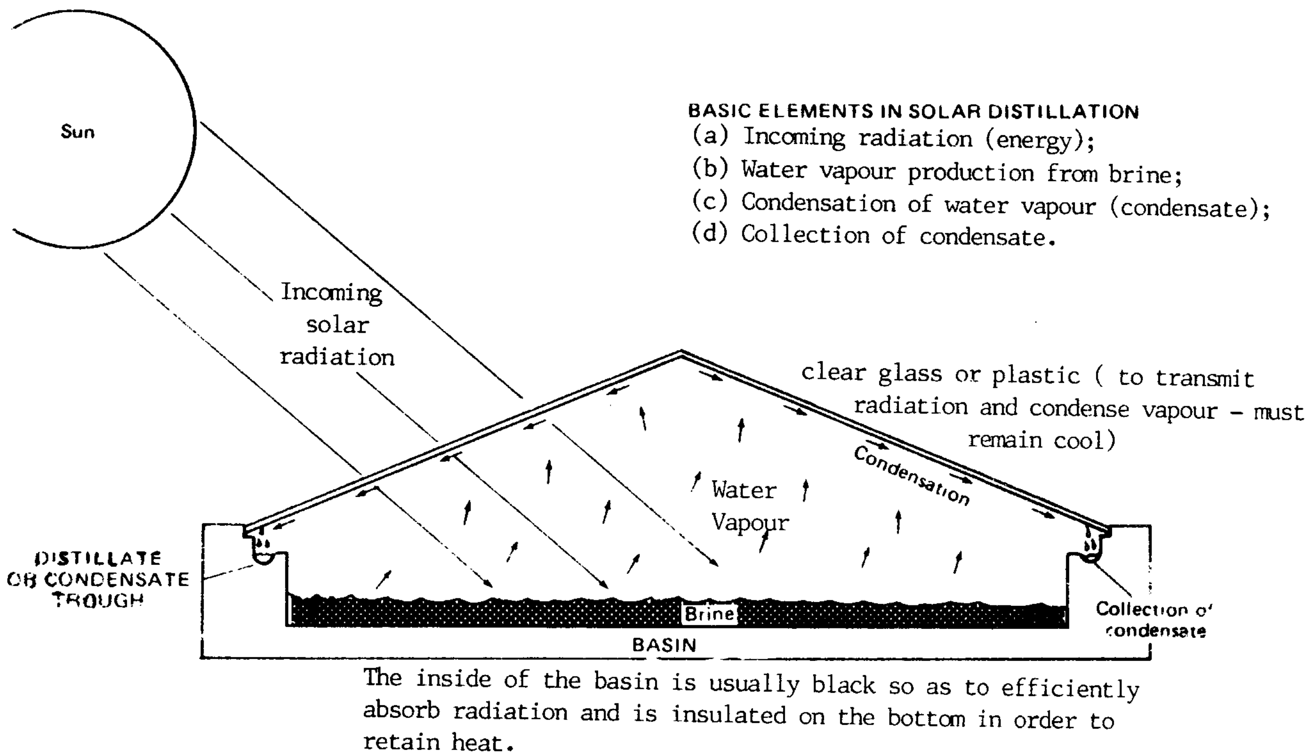
Photovoltaic cells that convert light from solar radiation directly into electricity so as to produce direct current could be used to operate motors and control the instruments in distillation and membrane desalination equipment. Over the last decade, growing interest has been shown in the ESCWA region to plants that are fully solar powered, and which eliminate the need for fossil fuel. The installation of such plants could well be appropriate for remote areas. Solar energy could be utilized to heat sea or brackish water through the use of solar stills in distillation or membrane processes. These work on the principle of using solar energy to increase relative humidity in a confined area, and enable the feed water to be distilled without boiling (see figure 30). Several factors affect the performance of the solar still, such as: solar radiation, the depth of brine in the basin, the cover material and its shape, ambient temperature, wind velocity and the temperature of the condensing surface. The use of solar energy in distillation, electrodialysis and reverse osmosis processes is still undergoing trial.

In the ESCWA region, which is characterized by a high average level of solar radiation intensity, limited applications of solar energy for desalination purposes exists. The first solar-powered sea water reverse osmosis facility was installed near Jeddah, in Saudi Arabia. The plant is powered by an 8 kilowatt (peak) photovoltaic array, which is about $93m^2$ in size and provides $2m^3/d$ of high quality drinking water using a hollow fine fibre membrane. In Qatar, there is a $6m^3/d$ reverse osmosis unit based on an 11.21 kW (peak) array, which incorporates an energy recovery pump. The SOLERAS (the Saudi Arabia-United States Joint Desalination Project), is an agreement between the United States and Saudi Arabia to co-operate in the field of solar technology and to facilitate technology transfer between the two countries. SOLERAS started solar desalination as one area of its programme. For this purpose, it contracted Catalytic Inc., and Scientific Applications Inc. to advance the technical and economic feasibility of large-scale solar-powered brackish water desalination plants. The system concept combines advanced solar energy and reverse osmosis membrane desalination systems. An average daily water production of 6,000 m^3/d is obtained from a two-stage reverse osmosis plant, with 90 per cent product water recovery. Water pre-treatment includes lime softening, filtration and ion exchange softening. Brine is disposed off through solar evaporation ponds. The electric power required to operate the system is generated by a solar system. Point focus and high temperature collectors, combined with a parabolic trough and medium temperature collectors provide thermal energy for the steam turbine generator. The power supply is complemented by a wind energy conversion system. The design concept for this system is illustrated in figure 31 (2). Kuwait has experimental plant that produces 10 m^3/day using the MSF technique, which is operated by solar energy (12 stages).

2. Wind energy (22)

Wind energy requires a wind turbine to harness it, which is similar to a water turbine except that it operates in the air. Because the density of air is relatively lower than that of water, rotor diameters are relatively larger than for water turbines (the density of air is equal to 1.29 kgm/m^3, while water density is equal to 1,000 kgm/m^3). The total power available in moving wind is $P = 1/2P\ AV^3$, where P is the air density, A is the area swept, and V is the free air velocity. However, only 16/27 of this total power is theoretically extractable, and the actual power extracted could well be less owing to mechanical and electrical losses. Accordingly, the power that can be generated from the different rotors depends mainly on their diameter. There are various kinds of rotors with different specifications that are based on shaft position, the mechanism for wind tracking, type of blades and their material properties, solidity ratio, etc. The higher the

Figure 30. Basic elements of a solar still



Source: This figure courtesy of the United States Agency for International Development, from O.K. Buros and others, USAID Desalination Manual (Washington, D.C., prepared for USAID by CH2M Hill International Corporation, 1980).

solidity ratio, the better the initial torque, but the lower the tip-speed ratio; also, the lower the solidity ratio, the higher the tip-speed ratio and the lower the torque. Water-pumping windmills typically have high solidity ratios, which give a sufficient initial starting torque. Electric-generating windmills have low solidity ratios to allow them to obtain the high rotational speeds that are required for electricity production. Generally, the efficiency of the windmill is a function of the tip-speed ratio. Moreover, the structure that holds the rotor should be rigid enough to support it against high winds, and it should have an adequate safety mechanism to protect the machine against strong wind storms.

There are several types of wind energy collectors. Some are horizontal, while others have vertical turbines capable of producing 4 MW that are commercially available. Wind energy systems coupled with reverse osmosis and electrodialysis desalination plants could prove to be economical in remote areas in arid regions where mean wind velocities are within relative use limits, as in the ESCWA region. In remote areas where conventional electrical sources are not available, and where brackish water desalination by reverse osmosis and electrodialysis is being considered, water pumping becomes an important factor and energy produced by windmills is an alternative that should be considered. Also, in the desalination process itself, some wind electric generators are currently being utilized to operate desalination plants and to connect a high pressure pump with the reverse osmosis process. Below are some of the potential applications for small-scale wind energy conversion systems.

(a) <u>Water pumping</u>

Pumping water for different purposes, especially using low cost energy, in order to lift brackish water is an important factor in the reduction of costs. Accordingly, there are two types of WECS that can be used to pump water: the direct mechanical pumping system, and wind electrical pumping.

For the direct mechanical pumping system, there are three basic types of windmills, namely:

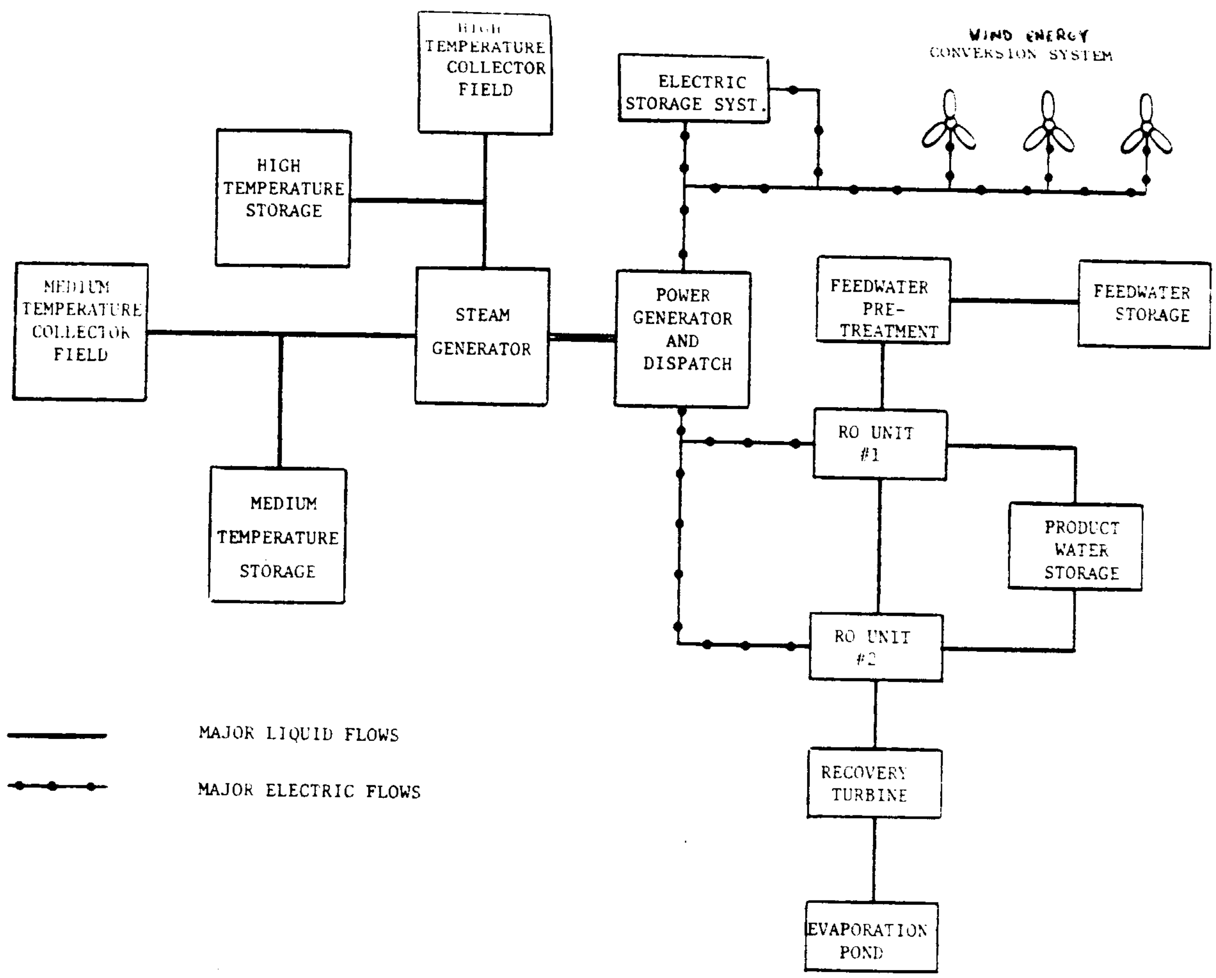
- Traditional multi-bladed windmills. These are the oldest type and still exist in some ESCWA countries. The Syrian Arab Republic manufactures them. By this system, the windmill rotor is directly or indirectly coupled to the pump. These windmills are characterized by their reliability, robustness and ease of maintenance.

- Modern multi-bladed windmills. These is a new type of windmill manufactured to take into account the new techniques. The windmills are similar to the traditional type, except that they are lighter, perform better and are simple to manufacture.

- Self-built windmills that are made of cloth and wood. They are characterized by the simplicity of their manufacture and their low cost though their performance is very poor.

The water discharge that is pumped daily can be calculated approximately as:

Figure 31. Design concept for a brackish water desalination system



Source: Proceeding of the Second SOLERAS Workshop, March 1981, Denver Colorado, U.S.A., Solar Water Desalination, Missouri: Programme Operating Agent. p. 203.

$$Q = \frac{0.7 \times V^3 \times D^2}{H}$$

where Q = discharge (m^3/d);

V = average daily wind speed;

D = rotor diameter (m);

H = total pumping head (m).

Assuming the power coefficient and hydraulic efficiency to be equal to 0.7, the power output of the windmill is equal to $P = 0.1\ V^3$ watts/m^2 of the swept area. For wind-electric pumping systems, all the electricity generated by the wind turbines can be used to power electric-driven pump sets that should be correctly matched. This has an advantage over the direct mechanical system in that wind turbines can be located on the site, irrespective of the water source location, but the direct system has the advantage of simplicity. Generally, wind-electric pumping systems consist of wind turbines (usually the two- to three-blade propeller type), generators and the associated electrical equipment, together with a tower.

(b) Water desalination using wind energy

Any consideration of wind power for desalination purposes must take into account the fact that wind speed and continuity are site-specific. Data on meteorological variables should be obtained so as to determine if wind power is possible, and in order to optimize the system design. The power produced by wind could be used to produce fresh water by the desalination of brackish water. The reverse osmosis process can be combined with wind power to desalinate brackish water. This is a fairly new application; on the other hand, little or no field-work has been done on wind powered electrodialysis. The energy required to produce one cubic metre by reverse osmosis wind-powered desalination can be determined by the formula:

$$E = \frac{S}{25R}$$

where E is the energy consumption required to produce one cubic metre (kWh/m^3);

S is the working pressure (bars);
R is the recovery ratio.

The above formula is valid when pump efficiency is 70 per cent. The cost of a unit of energy generated by two WECS that, if installed, have differently rated speeds in selected sites of the ESCWA region is given in table 31.

The economics of wind energy systems is related to mean wind speed. A wind pumping system is considered to be economical when the mean speed is more than 3.5 m/sec during the most critical months. Efforts are being made to design simplified wind machines that can be built in areas like the ESCWA region. Wind energy systems coupled with RO or EDR desalination plants could be economically feasible in some ESCWA countries where wind velocities are relatively high, provided that conventional energy sources are in short supply.

Table 31. Cost per unit of energy generated by two WECS with differently rated speeds, if installed in selected sites in the ESCWA region

Country	Site	O and M (m)	Capacity factor (F) MOD-A	Capacity factor (F) MOD-B	Unit energy cost mills/kWh MOD-A	Unit energy cost mills/kWh MOD-B
Bahrain	Muharraq	0.07	0.35	0.13	72	188
Democratic Yemen	Aden Airport	0.05	0.29	0.12	67	155
	Riyan Airport	0.05	0.24	0.10	80	186
	Scotora Island	0.05	0.59	0.33	33	56
Egypt	Ras Ghareb	0.04	0.67	0.33	24	48
	Hurghada	0.04	0.61	0.32	27	49
	Abo Ghossoun	0.04	0.37	0.15	44	105
	East Oainatt	0.04	0.43	0.17	38	93
Jordan	Ras Meneef	0.05	0.56	0.26	34	72
Kuwait	Al Ahmadi	0.07	0.42	0.15	60	163
Oman	Masirah	0.07	0.34	0.13	74	188
	Thumrait	0.07	0.41	0.22	62	111
Qatar	Doha	0.07	0.26	0.09	98	272
	Ras Rakan	0.07	0.48	0.19	53	129
	Halul Island	0.07	0.51	0.25	50	98
Saudi Arabia	Ras Tanura	0.07	0.25	0.08	101	306
Syrian Arab Republic	El Quneitra	0.04	0.56	0.36	29	44
	Palmyra	0.04	0.35	0.22	47	72
	Abou Kamal	0.04	0.27	0.17	61	93
	Qarachuk	0.04	0.21	0.13	78	122
United Arab Emirates	Jabal Dhanna	0.07	0.28	0.09	91	272
	Das Island	0.07	0.28	0.10	91	245
	Sharjah	0.07	0.30	0.09	85	272

Source: United Nations, Economic and Social Commission for Western Asia, Report on the Infrastructure Required to Disseminate Mature Solar and Wind Technologies in Selected ESCWA countries. Part II: Solar and Wind Technologies for ESCWA's Region (E/ESCWA/NR/86/5/Add.1).

V. ECONOMICS OF BRACKISH WATER DESALINATION

A. General

In general, the desalination techniques selected for arid areas must meet certain economic and practical criteria. As the demand for water resources increases, especially the fresh water, brackish water desalination is gaining acceptance for specific purposes in semi-arid and arid zones where water is scarce, thus releasing fresh water resources. As discussed in chapter II, the membrane techniques (EDR and RO) for brackish water desalination meet all the economic criteria required, therefore they are suited to the arid and semi-arid areas to which the ESCWA region belongs. Although the technology for brackish water desalination is available, many economic factors should be considered before it is used. In the ESCWA region, before any desalination water project is considered to be economically viable, a project should commence production upon installation, and should produce the desirable output in the quantities and quality planned over its entire life span. No doubt the utilization of water resources that were once considered too saline for human and agricultural use in an arid region such as ESCWA is to be looked upon as a gain. However, substantial capital investment is required, and the operation of the system will continue to require funds for energy, chemicals, labour, repair and replacement.

Desalting brackish water in order to increase water supplies depends on a host of factors, including the availability, reliability and cost of development of conventional ground and surface water, as well as the development of other non-conventional water sources such as rain water harvesting, sea water desalination and the feasibility of weather modification. A major advantage of brackish water desalination by the membrane technique is its low energy requirements as compared with other techniques. For ESCWA countries, EDR and RO offer an opportunity to provide fresh water supplies to rural and urban communities, as these processes are characterized by low energy consumption, simple operation and maintenance requirements that reduce the unit cost of the water produced, and the demand for highly trained labour. Their modular construction increases their expandability and reduces installation time in the field, as compared with other techniques. Moreover, reverse osmosis can be packaged as a compact water system that can be operated by a diesel engine or by gas turbines.

B. Technical considerations affecting desalination costs

Any major water desalination project in a water-short area, as is the case in many ESCWA countries, should be managed carefully, and based on a thorough water resource study and the formulation of a realistic economic development plan. Proper management includes activities that range from source selection and development to water usage and brine disposal. The criteria related to the production of fresh water from brackish water by the EDR and RO techniques depend on the following technical considerations.

1. Water demand and available resources

The economic and technical aspects of existing water resources should be examined carefully and a demand analysis should be carried out for all uses.

The Potential water resources available, including saline resources need to be assessed. The quantity, quality, cost development and consequences of economic development should be determined for all potential sources. In this respect, most ESCWA countries have developed a supply and demand analysis relating to their water supply.

A careful estimation should be made of demand, because the unit cost of desalinated water can affect water usage. The demand for water depends on many factors such as climate, culture, distribution facilities, different uses, accessibility and availability. In many of the Gulf countries, it is thought to be more economical to develop a system with two grades of water distributed separately, thus providing the distribution and usage of both potable and non-potable water.

2. Process selection

Many factors affect the selection of the desalination process; these are economic, and others such as (1):

(a) Raw water

There are differences in the design and costs of inland and coastal desalination plants that use brackish water. The intake of feed water at the sea coast will be affected, and a choice needs to be made as to whether a head structure in deep water should be built, or if a number of intake wells is needed near the coastline. In selecting intake locations, high quality raw water should be considered in order to avoid silt, sand and organic material. Intake wells, if properly constructed, will minimize such problems, especially when reverse osmosis techniques are used, they will also reduce pre-treatment requirements. When brackish water desalination is considered, a thorough water quality analysis must be made because the existence of certain constituents such as barium strontium and silica will adversely affect the recovery factor of the plant. In practice, it has been proved that EDR can maintain a higher recovery factor than RO, which has a significant effect on the economies of the operation. Raw water temperature is another important factor: warm temperatures result in structural problems for RO membranes (above 30^{o} C). However, it could be considered to be beneficial in desalination by ED, as it reduces the power required.

The quantity and quality of a brackish water soure can change daily and seasonally, and the extent of variation is important in the process of selection, design and the successful long-term operation of the facility. An example is the RO brackish water desalination plant at Ras Al Khaimah in the United Arab Emirates. The plant has a 1.5 Mgd capacity and was originally designed to produce 240 ppm of total dissolved solids in water when fed with 1,735 ppm raw water, but the TDS feed water has slowly increased to more than 4,500 ppm, owing to the depletion of brackish water resources. Accordingly, the product water salinity has increased to 1,100 ppm, and the recovery ratio has dropped from 90 per cent, as per the original design, to only 70 per cent. Hence, re-designing aspects that involve new criteria, such as 6,000 ppm TDS feed water and a recovery ratio of 75 per cent, have been developed. Accordingly, the quantity and quality of product water, which are determined beforehand, are affected by variations in the source.

(b) Plant site location

The factors that affect the choice of the site of a desalination plant, with a view to reducing the cost of the desalination process, include the following:

- Raw water availability;
- The brine disposal discharge method;
- The shortest distance to convey product to users;
- The availability of energy.

Other considerations pertaining to plant construction include:

- The geology of the site;
- Exposure to wind;
- Salt spray and flooding;
- The availability of cargo handling facilities, construction materials and labour.

The experience gained by the Gulf countries indicates that plants located on the coast present fewer problems than inland plants. In general, site costs, as a proportion of direct capital costs, decrease with the increase in plant size.

3. Desalination plant capacity

The availability of brackish water plays a major role in determining plant capacity. Therefore, a thorough assessment of brackish water resources must be carried out before the size of the plant is selected. If the quantities available are promising, then a decision regarding plant size can be taken.

In many of the Gulf countries, desalinated water is considered to be the major component in a water supply system that obtains only limited amounts of fresh water from reliable conventional sources. Optimum water mix costs probably result from maintaining the desalination plant at base load, and from meeting water peak demand with water from conventional sources. This would reduce both the cost of the desalinated water and the need for maximum safe storage capacity. However, in order to determine the size of a desalination plant, many factors must be taken into account:

- Long-term water supply and demand analysis;
- Industrial agricultural growth and consumption;
- Relative costs of the water supply;
- The reduction in overall efficiency of the plant over time;
- Decisions with regard to a double-piping system, with high and low quality water.

4. Need to ensure high reliability and efficiency

Desalinated sea and brackish water are used as major non-conventional water supplies for both domestic and industrial use. Therefore, reliable desalination plants with adequate storage are necessary. Also, efficient plants that are perhaps somewhat more complex in design and operation are needed, together with the basic method of solving serious operational problems and the expected benefits. According to concerned officials in the Gulf countries, efficiency and reliability are high when a number of desalination units are in operation, instead of one large unit. Of course, this could result in additional costs, but they would considered to be part of the improvement to reliability and efficiency.

Where no complementary water sources are available, a more reliable desalination plant, combined with adequate storage capacity will be necessary. Also, the more efficient the plant is, the lower its operating costs are, and this requires a complex design and operation of the plant. Hence, a careful economic analysis should be made regarding the efficiency and reliability of the plant.

5. Brackish water desalination brine disposal

As a result of desalination operations, brine is produced as a by-product. The brine is disposed of in the sea at a convenient distance from the intake, in areas near the coast. However, the disposal of brine creates a serious problem for inland sites where the desalinated water is brackish.

Brine is water with a high salt content that results from the desalination process, i.e. it has a higher TDS than the feed water. Usually it is too saline to be of use in agriculture, and contaminates surface and ground water. In fact, no inland project should proceed without a solution first being found to this problem, while in plants installed by the sea, brine is flushed into the sea. The solution proposed is that economic feasibility should be included as part of total desalination costs. Usually inland plant brine disposal solutions have an adverse impact on the environment. The suggested solutions are as follows:

(a) Evaporation in solar ponds, but the disadvantages of this are:

(i) The precipitated salt will be mixed with dust and fine particles when dust storms, which are frequent, blow;

(ii) Costs should be weighed against the expense of using and operating a high recovery system, as well as the size of the ultimate disposal system;

(iii) Solar ponds generally take up an appreciable area.

(b) The use of injection wells to dispose of the brine in high permeable zones, which would require a thorough hydrogeological investigation in order to delineate underground strata to ensure that existing ground water aquifers in the area are not contaminated;

(c) Piping the brine away to a safe distance for disposal;

(d) Transporting the final product away after evaporating the brine in ponds;

(e) The possible use of valuable chemical constituents recovered from the brine; this depends on local markets and on climatic conditions.

6. Desalinated brackish water pumping and conveyancing

When considering the cost of a desalination plant, it is usual to include pumping, conveyancing and the distribution of the water product. Conveyancing could be a significant factor when a desalinated plant is installed inland, but other factors such as the terrain, quantity of the water and the distances involved, etc., should be included. The following shows how water conveyancing costs can be calculated (1), while table 32 gives the water cost components from water wells of different depths.

(a)	Average annual rate	m^3/d
(b)	Total friction head loss	m/km x number of km
(c)	Net elevation difference	m
(d)	Total head required (b+c)	m
(e)	Energy required at o.y kWh per 3.8m^3 for each 30.5 m of head $\frac{o.y \times a \times d}{100}$	kWh
(f)	Energy cost at y mills per kWh (y .e/a)	cents/m^3
(g)	Total cost of pipeline	$/km x humber of km
(h)	Annual fixed charges at z per cent (z.g/a)	cents/m^3
(i)	Total cost for distance involved (f+h) ...	cents/m^3

Distribution costs can be considered to be the same for all types of desalination plants, while pumping costs depend on the quantity and depth from which the water is drawn. Leakage, unauthorized connections and broken metres add to the cost of the distribution system, i.e., to desalination plant costs. The quality of storage that forms part of the distribution system is well taken care of in Gulf countries, where it is sufficient to meet peak demand and it allows for a shut-down when the desalination plant is undergoing routine periodical maintenance or unplanned repairs.

7. Source of finance and foreign exchange

In some ESCWA countries, the need to augment conventional resources by desalination cannot be met because of the lack of finance given the high cost of desalination projects. Resorting to external assistance would carry a cost related to the ultimate repayments and savings. The repayment and saving of loans would, therefore, need to be included in the annual payment calculations. Also, foreign exchange for the purchase of spare parts and payment for repairs should be assessed over the life of a desalination plant.

8. Requirements for operation and maintenance

Skilled labour and personnel are required for the operation and maintenance of desalination plants. These are lacking for most operations in the ESCWA region, and are below the standard requirements needed to handle a complex modern desalination plant. The establishment of efficient training programmes is therefore necessary in order to provide the type of skills needed to operate and maintain the plant.

Table 32. Component of water costs from wells of different depths - synthesis of well data

TD	Q	Pump lift L	Q x TD	Cost of equipment	Total well cost	Energy cost[a]		Average annual energy cost (10^3\$)			Capital and replacement costs (10^3\$)			GW cost (\$US/10^3 m^3)		
						Diesel	Electricity	Hours of pumping			Well[b]	Pump[c]	Total including 4 per cent maintenance	Hours of pumping		
(m)	(m^3/h)	(m)	(10^3/h x m)	(10^3 \$US)	(10^3 \$US)	(S/h)	(S/h)	2,880	3,600	4,200				2,800	3,600	4,200
100	50	80	5	5.5	44.5	0.64	0.69	1.93	2.41	2.81	5.67	3.75	9.79	81	68	60
200	100	150	20	12.6	61.5	4.66	5.00	13.83	17.28	19.57	7.10	8.59	16.31	105	93	85
300	150	200	45	20.4	91.7	9.33	10.00	27.65	34.56	40.32	10.36	13.90	25.23	122	111	104
400	200	300	80	28.7	132.6	18.66	20.00	55.58	69.12	81.06	15.10	19.57	36.05	159	146	139
500	250	400	125	37.4	185.0	31.12	33.30	92.16	115.2	134.4	21.44	25.83	48.78	196	182	174
600	300	500	180	46.5	250.0	46.67	50.00	138.24	172.8	201.6	37.14	31.07	70.93	242	226	216
800	400	600	320	56.1	416.0	74.60	79.90	221.8	277.2	323.4	64.80	61.60	131.50	114	91	78
1,000	500	700	500	65.4	628.7	108.80	116.60	322.6	403.2	470.4	95.00	103.30	206.20	143	115	98

Source: A. Arar, "The means of increasing water resources", paper presented at the ACSAD-AFESAD-KFEAD Workshop on Water Resources Utilization in the Arab World, Kuwait 17-20 February 1986 (in Arabic).

a/ Energy cost is calculated on the basis of: overall pump efficiency = 0.7; overall pump efficiency x motor efficiency = 0.6; diesel oil cost = 60.62/1; electricity = 60.08/kWh.

b/ Capital cost I = 5; N = 20, replacement cost I = 10; N = 20.

c/ Capital cost I = 5; N = 20, replacement cost I = 10; N = 7.

Notes: TD = total depth;
Q = well discharge;
GW = ground water.

9. Availability of spare parts

In order to gain time and to minimize plant shut-down time, spare parts should be kept on hand. In the reverse osmosis operation installed to desalinate brackish water, membranes should be available for replacement at intervals of five years, while for electrodialysis manufacturers have designed replacements for use in intervals of 5 to 10 years.

C. Desalination plant cost evaluation

Desalination plant cost evaluation involves two major cost components: capital and operating costs. Capital costs include direct, and indirect capital and non-depreciable capital costs. The direct capital cost includes items such as site development (building, roads, grading etc.), the development of raw water equipment for the sources, the disposal of brine water and the development of energy sources. Indirect capital costs lower the interest costs incurred during construction start-up, contingencies and design or study and other fees. Included in non-depreciable costs are working capital (fuel on-hand, chemicals, materials, etc.), and land costs.

Annual costs contain elements that usually make up annual operating costs such as insurance, taxes, salaries, supplies, maintenance, energy, chemicals, membranes and filters, as well as fixed charges to cover capital depreciation. These costs are all combined in the plant factor (1):

$$\text{Plant factor} = \frac{\text{actual production}}{\text{rated (design) production}}$$

The annual unit production cost in \$US/m^3 for desalinated water is obtained through the following equation:

$$\text{Cost unit} = \frac{\text{annual recurring costs + annual fixed charges}}{\text{design capacity x 365 days x plant factor}}$$

From the above, it is worth noting that the plant factor plays an important role in both the economics and selection of the desalination technique. A 0.9 plant factor for a certain number of years means that the plant would be shut down for about 36 days (10 per cent of the time) (1).

D. Brackish water desalination costs in the ESCWA region

Brackish water exists in all ESCWA countries, but it does not constitute the main water supply source, rather, it is used to augment and supplement other water resources such as conventional fresh water, and/or it is blended with desalinated sea water. Brackish water desalination is currently employed in the Gulf countries through the use of techniques such as ED, EDR and RO. Table 33 shows the distribution of brackish water desalination operations within the ESCWA region as reported by member countries in response to a questionnaire distributed in 1986.

In a detailed economic analysis of a brackish water desalination project using electrodialysis, electrodialysis reversal or reverse osmosis techniques, it may be necessary to relate the short-, medium- and long-term price of water conservation and brackish water desalination options to the cost of supply, interest rates, operation and maintenance costs, etc., in order to obtain the average cost of the options. In order to perform a reliable analysis, information on appropriate costs, benefits, and inflation rates is needed; also needed is, technical information on performance characteristics, energy requirements, reliability, project length, etc. The factors that govern the economics of a brackish water desalination plant project are the size of the plant, the salinity of the raw water, the required quality of produced water, the location of the plant and the cost of any alternatives. Usually the major cost elements of a brackish water desalination plant are plant structure capacity, the distribution system, the disposal of brine, operation and maintenance, energy and the interest on borrowed money.

1. Brackish water desalination unit cost

At the United Nations Water Conference in 1977, a paper was presented which gave a comparison of the relative costs of the development of water supplies through the use of different non-conventional water resources, including brackish and sea water desalination, together with effluent reuse, as is illustrated in figure 32.

The reported costs of brackish water desalination in some of the Gulf countries are listed in table 34.

A comparison of the unit costs of available non-conventional water resources (desalinated water and treated municipal sewage effluent) in the ESCWA region is given in table 35.

The reported cost of brackish water desalination in Western Asia varied between $US 0.32 to $US 1.54 per cubic metre in 1986. These costs compare favourably with those shown on figure 32. Desalination costs are not considered to be excessive in the Gulf countries. It has been reported that the cost of distilled sea water in Qatar varies between 4.15 to 4.25 Qatar riyals ($1.14-1.16) per cubic metre at zero energy cost, while the cost of brackish water is 3.893 riyals ($1.01). The unit cost of desalination by distillation was estimated to be $US 0.87 per cubic metre in the United States in 1980, whereas it is more than one dollar in the ESCWA region, though the energy cost is low. Therefore, it can be assumed that the brackish water desalination unit cost is very favourable compared with that for the distillation of sea water for potable use, as reverse osmosis produces fresh supplies at 35 per cent of the cost of distillation. Also it could be considered to compete with that of effluent, which is not socially acceptable for domestic use.

In Kuwait the cost per 1,000 imperial gallons of desalinated distilled water in 1983/1984 reached KD 1.96 (70 per cent of total cost was energy cost) (KD 0.43/m^3), while brackish water extraction unit costs (1,000 imperial gallons) was KD 0.234 (KD 0.052/m^3). The breakdown for each is as follows (19):

Table 33. Brackish water desalination plants operated within the ESCWA region

Country and plant	Capacity 100 max. m^3/d	Number of hours of operation/yr	Total plant cost LC x 10^6	Number of Plant	Plant amortization LC	Percentage capital interest	Maintenance cost/yr LC x 10^6	Operating cost/yr LC x 10^6	Total fixed and variable costs LC x 10^6
Bahrain									
Ras Abu Jarjur	46	7,880	BD 39.5	20	BD 2.9	4	BD 3.346	BD 3.3	46.0
Kuwait									
Shegaya Military Camp	0.226 (2 units)	2,000	KD 0.14	20	KD 0.0143	8	O and M =	0.257 KD/M^3	...
Qatar									
Abu Samra	0.68	4,000	QR 3	20	0.15	10	0.05	0.2262	0.7786
Oman									
Abu Madhabi	0.05	4,013	OR 0.06	15	0.004	-	OR 0.022	OR 0.01	OR 0.036
Al Sa'adanat	0.05	3,364	OR 0.06	15	0.004	-	OR 0.022	OR 0.01	OR 0.036
Al Dharh	0.05	5,518	OR 0.06	15	0.004	-	OR 0.022	OR 0.01	OR 0.036
Saudi Arabia									
Rafha	8.5	-	SRls 125	-	-	-	SRls 5.6	-	-
Zulfi	18.0	-	SRls 152	-	-	-	SRls 7.0	-	-
Al Quwiya	6.5	-	SRls 82	-	-	-	SRls 4.3	-	-
Al Majma'a	9.0	-	SRls 90	-	-	-	-	-	-
United Arab Emirates									
Duraibat/Ras Al-Khaima	6,825 (3 units)	7,900	Dh 12.77	15	0.85	-	0.3	1.281	4.431
Umm Al-Quwin	9,100 (4 units)	-	Dh 14.2	15	0.95	-	0.35 (est.)	1.36 (est.)	2.66

Source: Data compiled by the United Nations Economic and Social Commission for Western Asia, based on responses to questionnaires sent to member countries in 1986.

Note: ... Data not available.

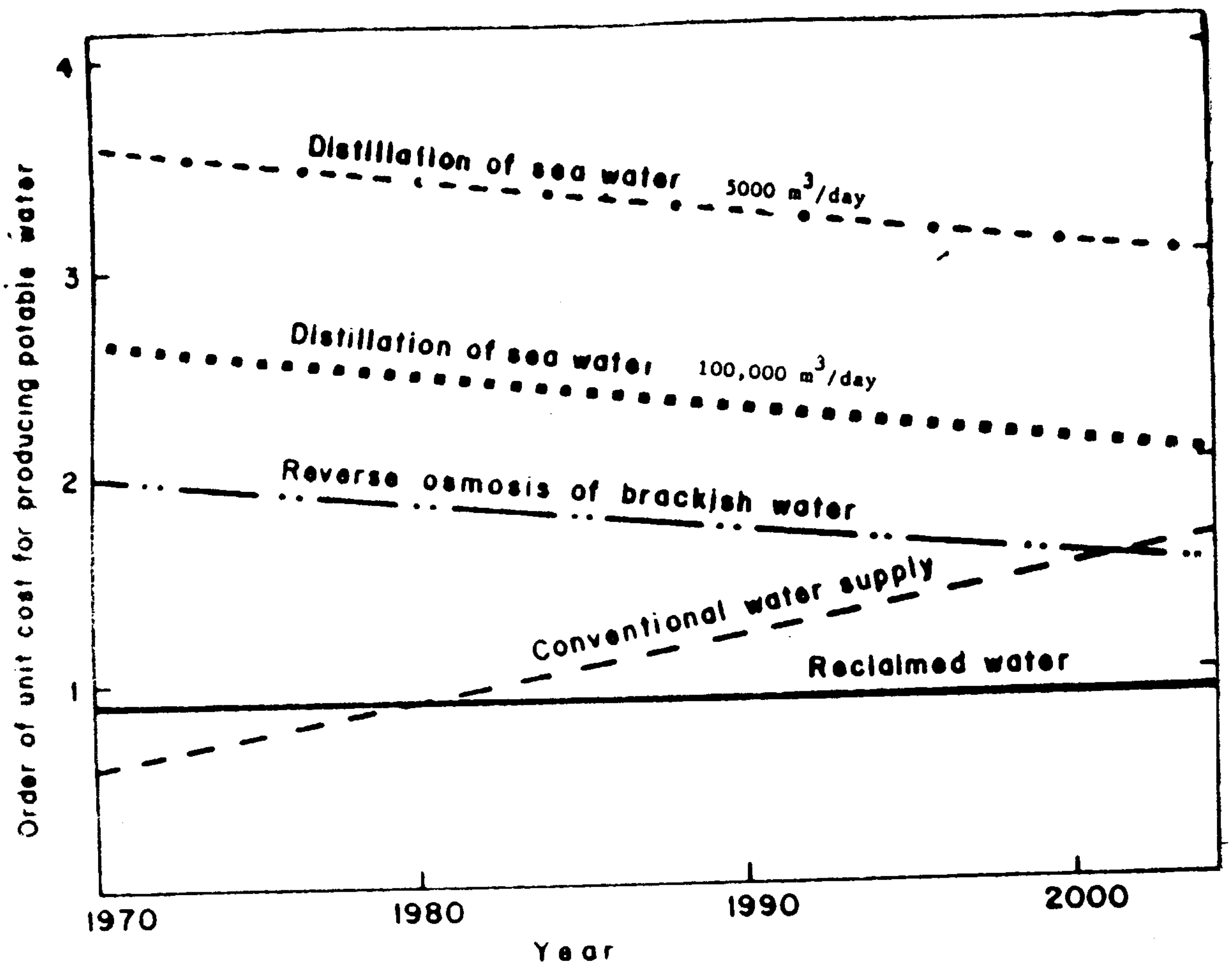
Table 34. Brackish water unit cost and energy unit cost in the ESCWA region

Country	Brackish water Unit cost per cubic metre		Energy cost per kWh	
	$US	Local currency	$US	Local currency
Bahrain	0.99	BD 0.375	0.043	BD 0.16
Kuwait	1.54	0.432 KD/m^3	0.064	KD 0.18
Oman	8.13-11.9	RO 3.13 to 4.6	0.08	RO 0.030
Qatar	1.06	QR 3.893	0.027	QR 0.06
Saudi Arabia	-	-	0.018	SRls 0.07
United Arab Emirates	0.44-0.32	1.62 to 1.18 Dh/m^3	0.02	Dh 0.075-

Source: Data compiled by the United Nations Economic and Social Commission for Western Asia, based on the response to questionnaires sent to member countries in 1986.

Note: Dh = United Arab Emirates dirham.

Figure 32. Estimated relative cost of water production with time of non-conventional water resources



Source: United Nations Water Conference, New York, December 1976, p. 11.

Table 35. Unit cost of non-conventional water resources in the ESCWA region

Country	Base year	Desalinated water unit cost range ($US/m^3)	Treated effluent unit cost range ($US/m^3)	Remarks
Bahrain	1986	0.998 (Br; RO)		
	1984	-	0.28	
	1984	-	0.84	
Egypt	1980	-	0.05-2.9	
Kuwait	1986	1.54 (Br; EDR)	-	
	1985	2.5 (SW; MSF)	0.33	
Oman	1986	8.13-11.9 (Br; RO)	-	Small units
Qatar	1986	1.06 (Br; RO)	-	
	1981	1.14-1.16 (SW; MFS)	0.24	Energy at zero cost
	1981	1.45-1.1.65		Energy at market cost
Saudi Arabia	1981	0.04 (Br; RO)	-	
	1979	0.72-1.23 (SW; MSF)		
	1982			
United Arab Emirates	1986	0.44-0.32 (Br; RO)		
	1982	1.00-1.45	0.3-0.4	

Source: United Nations Economic and Social Commission for Western Asia, based on responses to questionnaires sent to member countries in 1986; and United Nations, Economic and Social Commission for Western Asia, Waste water reuse and its applications in Western Asia (December 1985) (E/ESCWA/NR/84/L/Rev.1).

Item	KD/cost per imperial gallon
Capital	0.244
Operation	0.164
Energy	1.337
Maintenance	0.082
Overheads	0.109
Total	1.936
Brackish water withdrawal	
Capital	0.079
Maintenance	0.117
Overheads	0.038
Total	0.234

In brackish water desalination, unit costs using EDR depend on the total dissolved solids of the feed and the desired product, water composition and temperature. Brackish water enriched with a high concentration of silica and calcium sulphate using an EDR plant operating towards high recovery gives the system an advantage over RO. However, total capital costs for EDR increase with the number of stages. In the United States, the estimated unit cost of a cubic metre of EDR desalinated brackish water ranges from $US 0.26/m^3 to $US 0.47/m^3 for a 3,800 m^3/d plant of feed water TDS at 3,475 ppm. In the Gulf countries, the EDR unit cost is $US 1.54/m^3 (Kuwait) at 3,500 ppm. For reverse osmosis, the unit cost per cubic metre of desalinated brackish water ranges from $US 0.41/m^3 to $US 0.3/m^3 across the 3,800 to 95,000 m^3/d plant size range. In the Gulf countries, the unit cost per per cubic metre of RO desalinated brackish water varies from one country to another, but in general it fluctuates between $US 0.3/m^3 (TDS = 4,000 ppm with a 9,100 m^3/d plant capacity in the Untited Arab Emirates) to $US 1.01/m^3 (TDS = 4,000 ppm with a 680 m^3/d plant capacity in Qatar).

Table 36 gives a comparison of cost estimates for representative 3,800 m^3/d and 19,000 m^3/d brackish water desalination plants. The estimates are based on the following general assumptions that were used in the Oak Ridge National Laboratory study on desalination costs (Reed, 1981):

(a) Direct capital costs include: site development (but not land); infrastructure (common facilities, roads, intake and outfall systems, electrical utilities, etc.) and plant;

(b) Sites in continental United States. No major problems with brine disposal or the construction of intakes or outfalls;

(c) Indirect costs include interest incurred during construction, project management, overheads and profits. An interest rate of 11 per cent on capital was incurred during the construction period.

(d) Contingency cost plus an architect/engineering fee was 16 per cent of direct and indirect capital costs;

(e) Plant load factor: 85 per cent for sea water systems; 95 per cent for brackish water systems;

Table 36. Comparison of cost estimates for representative 3,800 m^3/d and 19,000 m^3/d brackish water desalination facilities

(Thousands of US dollars)

Plant capacity m^3/d (mgd)	3,800 (1) Brackish water RO[b/]	3,800 (1) Brackish water EDR[a/] 1	2	19,000 (5) Brackish water RO[b/]	19,000 (5) Brackish water EDR[b/] 1	2
Direct capital costs	976	1,262	1,436	3,841	5,348	6,113
Indirect capital costs						
Interest during construction	16	26	29	107	177	201
Working capital	49	53	72	192	267	306
Contingencies plus A and E [c/]	167	214	245	662	927	1,059
Total capital costs	1,208	1,555	1,782	4,802	6,719	7,679
Annual O and M costs						
Labour[d/]	60	59	59	119	119	119
Electricity[e/]	139	96	179	694	479	893
Chemicals and filters	52	22	22	186	97	97
Membrane replacement	62	19	28	233	92	339
Other	3	4	5	12	17	25
Total O and M costs	316	200	293	1,244	804	
Fixed charges[f/]	217	280	321	865	1,210	
Total annual costs	533	480	614	2,109	2,014	
Cost of water						
\$/m^3	0.40	0.36	0.47	0.32	0.31	
\$/1,000 gal	1.53	1.38	1.77	1.22	1.16	
Unit capital cost						
\$$m^3$	318	409	469	253	354	
\$/gpd	1.21	1.55	1.78	0.96	1.34	

Source: Adapted from S. A. Reed, Desalting Sea water and Brackish Water 1981 Cost Update.

a/ Recovery of 80 per cent, with a 95 per cent plant factor.

b/ Feed water quality should range between 2,000 to 5,000 ppm.

c/ Temperature of 21 °C.

d/ Labour cost to include 40 per cent for general and administrative overheads.

e/ Electrical consumption for 3,800 m^3/day plant should be assumed to be 2.1 kWh/m^3.

f/ A 30 year capital recovery at 18 per cent interest.

(f) Chemical costs in $/kg: anti-foam $2.31, sulphuric acid (100 per cent) $0.53, polyphosphate $3.98, sodium hexametaphosphate $0.70, potassium permanganate $1.43, sodium hydroxide $0.46, sodium sulphate $0.13, chlorine $0.30;

(g) Membrane replacement costs based on manufacturers' price and a membrane life of: 7.5 years for electrodialysis, 3 years for brackish water RO, and 5 years for sea water RO;

(h)Operation and maintenance labour cost based on inputs from manufacturers and users.

In addition to the above assumptions, the direct unit costs need the following requirements:

(i) Feed water quality should range between 2,000 to 5,000 ppm;

(ii) Recovery of 80 per cent, with a 95 per cent plant factor;

(iii) Temperature of 21 ^{o}C;

(iv) Labour cost to include 40 per cent for general and administrative overhead;

(v) Electrical consumption for the 3,800 m^3/d plant should be assumed to be 2.1 kWh/m^3;

(vi) A 30 year capital recovery at 18 per cent interest;

(vii) With EDR, TDS feed water No. 1 should be 2,016 ppm, while for No. 2 it should be 3,475 ppm.

Table 37 (Reed, 1981) gives a comparision of cost estimates for a representative 3,800 m^3/d and 19,000 m^3/d sea water desalination facility. The general assumptions are the same as those that underlay the unit cost estimates for desalinated brackish water, as mentioned above. The data provided to establish unit costs are:

- All cost estimates are in 1981 United States dollars;

- MSF plant: multi-stage flash unit using acid for scale control, performance factor = 12; maximum brine heater temperature at 121^{o} C; 85 per cent plant factor; energy using steam at a price of $2.31/million British thermal units (B.t.u.).

- Sea water reverse osmosis facility; 35,000 ppm TDS feed water; 80 per cent recovery; 85 per cent plant factor; temperature 21^{o} C; no energy recovery;

- MED: multiple effect horizontal tube unit using aluminum tubes, non-acid feed treatment; performance factor 12; maximum brine heater temperature of 75^{o} C; an 85 per cent plant factor; energy using steam at a price of $2.3 million B.t.u.;

- Electricity generated on site at a cost of 7.5 C/kWh for MSF and MED; purchased at 5.0 C/kWh for SW RO;

- Calculations based on a 30 year capital recovery, at 18 per cent interest.

In conclusion, all the data obtained on the unit cost of sea or brackish water desalination indicates that the brackish water desalination unit cost is the cheapest, especially when using EDR at a low salinity level (2,500 ppm), i.e. $0.31 per cubic metre.

Energy costs make up at least 20 per cent (for brackish water desalination using EDR) and reach 38 per cent (for sea water desalination using MSF) of total annual costs. Using renewable sources of energy (solar PV) the cost per cubic metre of desalinated brackish water ranges from $3.00 to $5.00, assuming reverse osmosis energy consumption is estimated at 2 kWh/m^3 and at 1.6 kWh/m^3 for electrodialysis. In the ESCWA study (E/ESCWA/NR/86/WG.1/3 (Part I), October 1986), the cost of a cubic metre of desalinated brackish water was found to vary between $US 2.50 to $US 3.5 (for solar PV), and between $US 1.5 and $US 2.5 (for wind energy), depending on the salinity level, with energy requirements rising with the level of salinity.

2. Economics of desalination plants in remote areas

Desalination techniques are highly specific and require sizeable investment. Because of the high costs involved, desalination is used for domestic and for some industrial purposes, rather than for agriculture. In remote areas and areas short of water, there is often a great need for desalination just to meet the basic drinking water and sanitation needs of people and livestock. There are many areas in the ESCWA region where only brackish water is available for drinking purposes. Therefore, there is considerable scope for introducing small-scale desalination plants that treat brackish water in rural areas where alternative supplies are extremely limited, but this would require considerable planning in order to achieve long-term success, and subsidies to reduce costs.

In remote areas where brackish water desalination is considered, and where no national electricity grid is available, electrodialysis competes in terms of capital costs with reverse osmosis (see table 37), because it can utilize a direct current from a photovoltaic array without power conditioning. Furthermore it does not require high pressure and is more tolerant to changes in water quality. It is expected that the photovoltaic array costs associated with RO or EDR will decrease their desalination costs using these supplies, in particular in remote areas, so as to become competitive with or cheaper than diesel systems where fuel costs are high. Wind power systems would be attractive for remote areas in the ESCWA region where average wind speeds are six m/s or higher. For higher average wind speeds, the energy output would be considerably greater (as it increases as the cube of wind speed). However, even in places with good wind speed, it is likely to be less reliable than solar energy and a diesel generator back-up may be required. In conclusion, solar photovoltaics has a number of advantages over wind, especially for small systems.

Table 37. Comparison of cost estimates for representative 3,800 m^3/d and 19,000 m^3/d sea water desalination facilities

(Thousands of US dollars)

Plant capacity m^3/d (mgd)	3,800 1 MSF a/	3,800 1 SWRO b/	3,800 1 MED c/	19,000 5 MSF a/	19,000 5 SW RO b/	19,000 5 MED c/
Direct capital costs	6,024	4,270	5,110	19,726	17,260	15,385
Indirect capital costs						
Interest during construction	497	144	164	1,808	825	1,265
Working capital	439	214	89	1,926	863	305
Contingencies plus A and E	904	740 d/	741	2,959	3,032 d/	2,313
Project management overheads and profit	2,259	..	1,916	7,397	..	3,776
Total capital costs	10,123	5,368	8,020	33,816	21,980	25,036
Annual O and M costs						
Labour e/	238	119	217	305	203	252
Energy - steam	495		446	2,475		2,230
Energy - electricity f/	113	590	140	565	2,947	700
Chemicals and filters	57	81	28	286	372	140
Membrane replacement	57	81			1,396	
Other	36	35	84	86	150	270
Total O and M costs	939	1,135	915	3,717	5,068	3,592
Fixed charges g/	1,822	966	1,444	5,907	3,956	4,508
Total annual costs	2,761	2,101	2,359	9,624	9,024	8,100
Cost of water						
$/$m^3$	2.37	1.81	2.03	1.65	1.54	
$/1,000 gal	8.90	6.77	7.60	6.20	5.82	
Unit capital cost						
$/$m^3$	2,672	1,123	2,118	1,785	1,156	
$/gpd	10.12	5.37	8.02	6.76	4.40	

Source: Adapted from S. A. Reed Desalting Sea water and Brackish Waters, 1981 Cost Update.

a/ Feed water quality should range between 2,000 and 5,000 ppm.
b/ Recovery of 80 per cent, with a 95 per cent plant factor.
c/ Temperature of 21° C.
d/ Labour cost to include 40 per cent for general and administrative overheads.
e/ Electrical consumption for the 3,800 m^3/d plant should be assumed to be 2.1 kWh/m^3.
f/ A 30 year capital recovery at 18 per cent interest.
g/ With EDR, TDS Feed water No. 1 should be 2,106 ppm, while for No. 2 it should be 3,475.

Table 38. Estimated range of capital and water costs from experimental desalination plants using renewable sources of energy

	Total capital cost, 1984 ($/m³/d installed capacity)		Annual capital cost (amortized at 12 per cent for 20 years and 18 per cent for 10 years)	Cost of water (90 per cent plant factor $/m³ $/1,000 gal)
	Sea water	Brackish water	($/yr)	
Solar still a/	32,000		4,300-7,100	13.00-22.00 (49.00-82.00)
Multiple-effect solar still b/	16,000		2,100-3,600	6.50-11.00 (25.00-41.00)
Vapour compression c/	20,000			
plus solar PV d/	20,000			
Total	40,000		5,400-8,900	16.00-27.00 (16.00-100.00)
Small multi-stage flash e/	10,000			
plus solar thermal f/	18,000			
Total	28,000		3,800-6,200	11.00-19.00 (43.00-72.00)
Membrane distillation j/	5,000			
plus solar thermal k/	12,000			
Total	17,000		2,300-3,800	7.00-12.00 (26.00-44.00)
Reverse osmosis g/	12,000	4,000	SW: 3,800-6,200	SW: 11.00-19.00 (43.00-72.00)
plus solar PV d/	16,000	4,000	Br: 1,100-1,800	Br: 3.00-5.00 (12.00-21.00)
Total	28,000	8,000		
Electrodialysis h/		5,000		
plus solar PV i/		3,000		
Total		8,000	Br: 1,100	Br: 3.00-5.00 (12.00-21.00)

Source: United Nations, Department of Technical Co-operation for Development. The Use of Non-conventional Water Resources in Developing Countries, Natural Resources No. 14, New York, 1985, (United Nations publication, Sales No. E.84.II.A.14), pp. 109-110

Note: Desalination equipment cost estimates are based on 1984 price quotations for a 10 m^3/d desalination plant that is assumed to produce only 4 m^3/d when powered by solar energy sources, without storage, plus corresponding solar thermal or photovoltaic energy sub-systems. Estimates provide only approximate ranges of costs, which could easily change depending on assumptions and technological breakthroughs. They are based on experimental prototype or sub-system costs, and therefore should not be considered to represent actual commercial costs.

a/ Solar still producing 3.3 1/d/m^2 is based on recent Australian prices of $100/$m^2$.

b/ Improved multi-effect solar still is a 10-stage unit producing 26 1/d/m^2. Energy equipment costs are estimated at $400/$m^2$.

c/ Specific energy consumption for vapour compression unit estimated at 10 kWh/m^3.

d/ Solar PV energy equipment costs based on $12/W, with some battery storage.

e/ Small multi-stage flash unit has estimated energy consumption of 130 kWh/m^3 for 10- to 12-stage unit.

f/ Solar thermal parabolic trough (or evacuated tube) energy equipment costs estimated at $300/$m^2$, 120° C brine temperature, with 50 per cent collector efficiency.

g/ Reverse osmosis energy consumption estimated at 8 kWh/m^3 for sea water and 2 kWh/m^3 for brackish water.

h/ Energy consumption for electrodialysis brackish water applications estimated at 1.6 kWh/m^3.

i/ Solar energy equipment costs based on $10/W, without storage.

j/ Membrane distillation equipment costs are only estimated, as this technology is not yet commerically available. Estimates based on energy consumption of 70 kWh/m^3.

k/ Solar thermal flat plate collector system based on equipment costs estimated at $300/$m^2$, 85° C brine temperature and 30 per cent collector efficiency.

VI. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. Summary and conclusions

The rapid increase in population, the growth of urban areas, and the steady rise in living standards have dramatically increased the demand for water in the ESCWA region. This, in turn, has posed special problems, especially in arid and semi-arid zones, for water supply systems that seek to meet this demand from only a limited water potential. It has also created growing technical, economic and organizational difficulties for different water institutions.

In the light of the limited water resources available in most member States of the ESCWA region, the augmentation of the conventional water supplies by non-conventional water development techniques has become an overriding concern in the region. Present technologies have made desalination viable, with quality matching the high quality of fresh water resources.

Therefore, brackish and sea water desalination can substantially reduce the overall water scarcity in the region. Desalinated brackish water can be used for domestic water supplies, provided that adequate resources are available over the water project life. Hence, the availability of brackish water is very important, because continuous withdrawal from limited brackish water resources would adversely affect quality and, hence, the efficiency and reliability of the desalination plant that could be the sole source of water in a particular area. It is certain that brackish water desalination would augment water supplies in arid areas like Western Asia.

Raw brackish water resources can be used for drinking, though subject to certain quality limitations, for the irrigation of selected plants able to support high salinity aqua-culture, or for blending with distillate desalinated sea water in order to enrich its quality with certain constituents that have been de-mineralized during desalination, and which meet WHO potable water standards. Though desalinated brackish water would be feasible and might help solve the problems encountered in remote water-short areas, it is considered to be an expensive technique unless it is subsidized by governments or justified because of urgent demand: for a remote resort hotel, a remote strategic industry, severe remote water-short areas where electrodialysis reversal combined with photovoltaic cells is considered to be the cheapest method under such conditions.

1. Desalination

The increase in water consumption and the depletion of existing conventional water resources has led to considerable interest being generated in brackish and sea water desalination over the last 30 years. The cost of desalination is generally not competitive with that of fresh water. Continued development is expected to reduce the failure cost of desalination to levels that are comparable with those of fresh water treatment and production, though increases in energy costs may work in the opposite direction. Desalination systems can be separated into those that employ a phase change, such as distillation, which is very common in the Gulf countries of the ESCWA region, and those which separate water and dissolved salts within an aqueous phase, such as electrodialysis reversal and reverse osmosis, which are commonly used for brackish water desalination.

The science and art of desalination has progressed only by limited stages since the first multi-stage flash evaporation plant was installed at the Shuwaikh Plant in Kuwait in 1957. Over the same period, Kuwait conducted experiments with an electrodialysis membrane system that probably constituted the first membrane plant to be installed in the region. Research and development have since resulted in the discovery and adoption of more sophisticated and efficient electrodialysis, i.e. electrodialysis reversal and, later, the development of reverse osmosis systems. Since 1960, little progress has been made in the development and general acceptance of new technology in the distillation process. For the last 30 years the multi-stage flash evaporation technique has remained the most popular and successful system for the economical production of large quantities of low-salinity water suitable for potable and industrial use. Among membrane techniques electrodialysis is the most popular system for desalinating water for various industrial applications, and it is in common use in the soft drinks industry owing to its reliability and its low capital and operating costs. The development of a technique by which the electrical polarity of the membrane stack was reversed at regular intervals resulted in a considerable increase in membrane reliability, and a reduction in operating costs. This technique has played a major role in establishing the popularity of the EDR system in the face of competition from reverse osmosis - the other major membrane system. The latter became popular for use in small desalination systems. As membrane science developed, and membranes became more reliable, the process was used for a greater range of brackish waters. As membrane reliability improved, the larger and more important desalination systems turned to the reverse osmosis technique. At present, many companies manufacture wide ranges of all types of excellent membranes that are suitable for sea as well as for brackish water. They show considerable tolerance to mis-use, and render service over a period of about five years. Reverse osmosis has begun to challenge the multi-stage flash evaporation system. Considerable controversy exists regarding the merits and disadvantages of the two systems, but no one is definitive. Generally, distillation and reverse osmosis are used for sea water desalination, while reverse osmosis and electrodialysis reversal are used for brackish water desalination. However, the selection and use of those processes are very site-specific, and they have to be carefully selected. One of the major considerations in the selection of a desalination process is its cost. Although there have been considerable efforts to reduce costs, desalinated water is still expensive. The process is inherently energy-intensive in energy costs.

2. Brackish water resource availability

An assessment of the available brackish water resources is considered to be a prerequisite for any desalination plant construction, and surface and ground brackish waters are abundant all over the ESCWA region. An assessment of their quantity is available in some ESCWA countries, in particular the Gulf countries like Bahrain, whose conventional water resources are entirely brackish. Assessments are absent in countries that depend on other fresh surface or ground water resources. Table 39 shows the relative abundance of brackish water resources, and their uses in different ESCWA countries.

Table 39. Relative brackish water availability in the region

Country	Coastal	Inland			Assessment	Uses
		Surface	GW			
Bahrain	X	–	X	X	Yes	Drinking, blended with desalinated sea water, desalinate
Democratic Yemen	X	–	X	–	No	Agriculture, domestic
Egypt	(little)	–	–	X	Not used	
Iraq	–	(high)	(high)	(high)	No	Drinking and domestic (most of it unused)
Jordan	–	X	X	X	No Approximate	Agriculture
Lebanon	–	–	–	–	No	–
Kuwait	X	–	X	–	Yes	Agriculture, blended with distillate water
West Bank and Gaza Strip	X	X	X	X	Approximate	Agriculture
Qatar	X	–	X	–	Yes	Agriculture, blended with distillate
Oman	X	–	X	–	Approximate	Agriculture, blended with distillate
Saudi Arabia	X	–	X	X	Approximate	Agriculture, blended with distillate, desalinated for potable purposes
Syrian Arab Republic	X	X	X	X	Approximate	Agriculture
United Arab Emirates	X	–	X	–	Yes	Agriculture, desalinated for domestic uses
Yemen Arab Republic	X	–	–	–	No	Agriculture

Source: Data complied by ESCWA.

It is worth noting that brackish water supplies from return flows from agricultural irrigation drainage are collected by appropriate drainage techniques and are allowed to return to natural streams where they undergo some form of natural purification before being re-extracted (Egypt and Iraq). However, such a system must be closely monitored and return flows treated to a certain degree before they are discharged into streams, in order to avoid contamination of other water resource.

3. Brackish water desalination in the ESCWA region

The most important aspect of brackish water desalination relates to the processes that are available for treatment, according to the quality criteria for both the feed raw water and the final product. The capabilities of different desalination processes are depicted in tables 6 and 7. Reverse osmosis and electrodialysis reversal techniques no doubt offer the most appropriate technologies for brackish water desalination given their simplicity of structure, ease of maintenance, operation and installation, and energy saving features; they are also the cheapest of the desalination techniques. Also, electrodialysis is competitive in terms of capital costs with reverse osmosis with regard to brackish water applications, and can utilize direct current electrical output, without high pressure, as well as being more tolerant to water quality. Small-scale desalination units powered by solar photovoltaic systems are adequate for remote areas in the ESCWA region. There are requirements for the desalination of brackish water that can only be decided upon in the light of the strategy developed for desalinated brackish water use; undesalinated brackish water also has its uses, and these could be considered in accordance with a long-term supply and demand analysis.

ESCWA countries that are active in the field of sea and brackish water are the Gulf countries, including Bahrain, Kuwait, Qatar, Oman, Saudi Arabia and the United Arab Emirates. Desalination started in these countries in the early 1950s. Table 40 gives a summary of all the brackish water desalination activities in the region in 1986.

Table 40. Brackish water desalination activities in the ESCWA region in 1986

Country	No. of plants	Plant types	Capacity (Mm^3/d)	Feed water salinity (ppm)
Bahrain	1	RO	41.4	10,000
Kuwait	1	EDR, RO	0.113	3,000-3,500
Qatar	1	RO	0.68	3,500-4,000
Oman	3	RO	0.079	3,000-5,000
Saudi Arabia	4	RO, EDR	28.0(RO)	2,000-7,000
United Arab Emirates	2	RO	15,925.0	3,000-4,000

Source: United Nations Economic and Social Commission for Western Asia, based on data obtained in response to questionnaires sent out in 1986.

4. Energy

The multitude of factors that affect desalination process energy are of the utmost importance for they cover 15 to 40 per cent of the total annual cost of most of the established desalination plants, and between 15 and 85 per cent of the daily operation and maintenance costs of the produced water. Energy costs increase proportionally with plant size. However, for brackish water, reverse osmosis and elctrodialysis consume less energy per cubic metre of desalinated water.

Desalination with renewable energy is limited almost entirely to solar stills used in locations around the world. Numerous experiments, using solar wind energy, have been carried out in conjunction with other techniques, but they have seldom been commercially competitive with the desalination facilties powered by conventional means.

Unlimited quantities of brackish water are used in Gulf countries for blending with desalinated sea water to compensate for mineral constituents lost during the desalination process.

It is expected that the photovoltaic array costs associated with reverse osmosis or electrodialysis will decrease, thus providing the opportunity for cheaper brackish water desalination to become more competitive with diesel fuel systems in some parts of the ESCWA region. Wind powered systems are attractive for use in remote areas in the ESCWA region, but they are less reliable for solar-based energy systems, especially for photovoltaic systems that have a number of advantages over wind for small-scale desalination plants.

In non-oil-producing countries, two additional factors should be considered: that desalination requires foreign exchange for the purchase of equipment, and that the process involves high energy use.

5. Economics

Although the technology of brackish water desalination is available and has been proved, economic considerations limit its use, though this may be the only alternative in remote locations, or for particular purposes. As the demand for existing resources in water-short areas increases, brackish water desalination is expected to gain in importance.

The use of brackish water desalination to increase water supplies depends upon the availability, reliability and cost of developing conventional water resources, surface and ground sources of water, and upon the cost of other non-conventional techniques. If water of a desired quality can be supplied by other methods at less than the cost of brackish water desalination, then there is no need for desalination. On an economic basis, desalinated brackish water can be justified for domestic purposes. In addition to the brackish water unit costs reported by different ESCWA countries in 1986, table 41 gives the plant size and feed water salinity of operational plants in the region.

Table 41. Brackish water desalination unit cost

Country	Unit cost ($US/m^3)	Plant capacity (Mm^3/d)	TDS (ppm)
Bahrain	0.99(1986)	41.4	1,800-12,000
Kuwait	1.54(1986)	0.113	3,000-3,500
Qatar	1.06-11.9(1986)	0.68	3,500-4,000
Oman	8.13-11.9(1986)	0.079	3,000-5,000
Saudi Arabia	0.04(1981)	28 (RO)	2,000-7,000 2,000-5,000
United Arab Emirates	0.44-0.32(1986)	15,925	3,000-4,000

Hence, the unit cost of desalinated brackish water is competitive with that of other non-conventional resources, in particular with the unit cost of the reuse of effluent, which is socially unacceptable, where unit costs were estimated at $US 0.4 m^3 in 1985. The reuse of effluent and the desalination of brackish water have an important economic factor in common, in that both can be used mainly for irrigation if they are not considered suitable for drinking purposes. It is believed that desalinated water unit costs in Oman are high ($US 8.13-11.9) because of the small capacity of the unit and the relative high costs of operation and maintenance.

It should be emphasized that brackish water in Western Asia would be considered when its availability is assured especially inland brackish ground water resources. For brackish ground water, depletion will result in a deterioration in quality and in an increase in total dissolved solids owing to continual pumping which the plant was not originally designed to cope with, and this has an adverse effect on plant performance. In the case of coastal brackish water desalinaion plants, the sea intrusion interface should be calculated and pumping should not exceed the recharge, because the inward interface shifting position will result in sea water invasion.

In any inland brackish water desalination plant, brine disposal discharge should be reckoned from the economic and environmental point of view in order to avoid salt accumulation and the possibility of contaminating the land as well as other water sources.

B. Recommendations

Brackish water desalination has been undertaken in the Gulf countries for a considerable period of time, though only on a limited scale. Only recently in the United Arab Emirates has a large-scale capacity of this source of supply been commissioned. The availability of other sources of water supply in other countries precluded wider applications. However, the development of new technologies and the rising cost of water developed by conventional methods could change the outlook with regard to brackish water desalination, which is used mainly for potable and industrial purposes. Therefore, the following recommendations are made for applications in the ESCWA region:

1. For brackish water utilization, it is of the utmost importance that some provision be made in the national objectives and policies for water resources of the country. The necessary planning must be enacted to promote and control brackish water reserves. One of the most important aspects of brackish water utilization is the safe and efficient management of resource development within the whole water plan of the country. It is possible that brackish water be kept in hand as a strategic reserve, or that it be used in irrigation applied to certain plants that are tolerable to salinity, or that it be used to augument conventional water resources, either by blending with distillate water or by desalination. The planning aspects that should be considered for brackish water utilization include potential users, the required qualities for potential use, the quantity and period of need, brackish water supply reliability, the compilation of data on existing demand and supply, and the study of the physical and engineering aspects of utilization options.

2. Brackish water desalination is a very site-specific operation. It mainly depends on availability and the ease of development. If sufficient resources could be ensured, its unit cost could be justified for potable and industrial use in urban and rural areas, but not for agricultural purposes.

3. Despite the substantial costs involved in the desalination process, the availability of desalinated water could be an economic advantage in rural areas in the ESCWA region where water is scarce, and where it is often transported by trucks and sold at unit costs that exceed those for desalinated water, though it still needs to be subsidized by the government.

4. The utilization of brackish water resources for different purposes requires intensive quantitative and qualitative assessment of brackish water sources that should be undertaken to avoid any future surprises such as ground water depletion, an acute change in salinity levels, an inward shift of the sea water interface. Modern technology, through the use of remote sensing, has allowed the identification of the interface by taking advantage of the thermal properties of fresh saline boundary lines.

5. In order to avoid pollution or contamination, sources should be thoroughly examined. Accordingly, it would be better to develop feed water sources, quantitatively and qualitatively, in order to characterize them clearly, and hence to move on to a final selection and/or design of the desalination plant that could modify pre-treatment and/or the capacity required.

6. The produced water desired should be studied carefully by taking into consideration drinking water standards, the preferences in taste of the population using the water, and the type of post-treatment to be used.

7. The quality of brackish feed water should be thoroughly analysed as this affects the process selection of either RO or EDR. Raw water enriched with a

silica constituent is more tolerant to EDR than RO, pre-treatment and post-treatment. The presence of some constituents such as barium, strontium and silica can adversely affect the recovery factor of the plant.

8. The reliability and efficiency of plant operation should be of the utmost concern. This is important in the ESCWA region, where it could be very difficult to mobilize a sufficient number of trained operating personnel, especially when the plant is the main source of water supply. Reliability is enhanced by a proper design, good materials and simplicity of operation.

9. Brine disposal from plants located inland can be a serious problem. The improper discharge of brine can contaminate fresh surface or ground water. It is too saline to be used for irrigation, so disposal options are limited. The methods used to dispose of the brine are as follows:

- Evaporation ponds, or a conventional thermal evaporator;

- Injection into existing confined zones of very saline ground water that require careful selection and proper design in order to avoid the contamination of fresh ground water aquifers;

- Transportation of the brine to a saline water body, i.e. the sea.

It must be borne in mind during planning that as yet there has been insufficient experience in inland brine disposal.

10. Desalination with renewable energy: The system costs operated by renewable energy are still high. Photovoltaic systems associated with reverse osmosis or elctrodialysis reversal should begin to compete with diesel systems in remote areas, especially when a national electric grid is not present.

11. Research work in the area of the desalination of brackish water in ESCWA region could usefully concentrate on the following:

- Improving membrane characteristics, or introducting new ones to be used in reverse osmosis plants;

- Reducing the unit cost of brackish water desalination through the use of renewable energy;

- Experimenting with plants that are tolerable to salt;

- Intensive research on aqua-culture in brackish water.

12. Dissemination and exchange of information and expertise among member countries is necessary in order to assist each other in this field.

13. Training programmes at the technician level on desalination plant operation and maintenance is necessary so that each country can develop its own cadre of trained personnel.

Table 42. Technical assistance requirement

Country	Assistance required		
	Brackish water investigations	Desalination technologies	Training
Bahrain	Not required	Not required	Required
Democratic Yemen	Required	Required	Required
Egypt	Required	Required	Required
Iraq	Required	Required	Required
Jordan	Not required	Required	Required
Oman	Not required	Required	Required
Syrian Arab Republic	Not required	Required	Required

ANNEX

QUESTIONNAIRE ON BRACKISH WATER DESALINATION WITHIN THE ESCWA REGION

The limitations of conventional water resources and the worry that they will fail to meet demand in the long run has led many ESCWA countries to investigate alternative water resources such as the desalination of sea and brackish waters and sewage reuse.

Over the last decade, hydrogeological investigations have proved the availability of brackish water in different parts of the ESCWA region. The Water Resources Subprogramme of the ESCWA Natural Resources, Science and Technology Division, in compliance with the Mar del Plata Action Plan and the International Drinking Water Supply and Sanitation Decade, therefore, envisages the current study on the desalination of brackish waters for the production of fresh water for domestic and agricultural water supplies in selected countries of the ESCWA region.

The study is designed to include a list of available brackish waters in the region, with a brief review of desalination technologies. The sources of new and renewable energy and their applicability in desalination will be investigated. Subsequently, an indicative cost-benefit analysis will be prepared for combinations of brackish water salinity levels, project size and sources of energy.

Conclusions will be drawn identifying the needs for technical assistance that ESCWA might be able to offer to member States, its type and duration. Recommendations will also be developed for the use of brackish water supplies for domestic and agricultural purposes, and the advantages versus disadvantages of various desalination methods and technologies will be analyzed.

In order to carry out this study, the enclosed questionnaire has been prepared in as brief a form as possible, to collect the needed information. The agencies concerned are kindly requested to fill it at their earliest convenience.

Questionnaire on brackish water desalination

Governmental Body:

Date: ______________________

I. If significant brackish water resources of 2000 to 5000 ppm salinity are available, please indicate:

No.	Brackish Water Data / Locality	Quantity		% of Total Country Water Resources	Use			Salt Content	Beyond Limits		Aquifer		Remarks
		Q	M^3 or M^3/h		Direct	Mixed	M^3 or M^3/h	ppm	Anions or Cations	ppm	Name	Depth (M)	
1.													
2.													

Questionnaire continued

No.	Brackish Water Date / Locality	Quantity		% of Total Country Water Resources	Use			Salt Content	Beyond Limits		Aquifer		Remarks
		Q	M^3 or M^3/h		Direct	Mixed	M^3 or M^3/h	ppm	Anions or Cations	ppm	Name	Depth (M)	
3.													
4.													

Questionnaire continued

No.	Brackish Water Data / Locality	Quantity: Q	Quantity: M^3 or M^3/h	% of Total Country Water Resources	Use: Direct	Use: Mixed	Use: M^3 or M^3/h	Salt Content: ppm	Beyond Limits: Anions or Cations	Beyond Limits: ppm	Aquifer: Name	Aquifer: Depth (M)	Remarks
5.													
6.													

II. If brackish water desalination plants are in operation or under construction, please indicate:

Plant Technical Data \ Plant Name & Locality					Remarks
Operational or Under Construction					
Desalination Plant Type (R.O., Electrodialysis, etc).					
Maximum Daily Capacity M^3/d					
Average Annually Number of Hours of Operation					
Average Daily Production (M^3)					
Total Cost of Plant (local currency)					
Plant Amortization: No of Years					
Plant Amortization: Amount Per Year					
Interest on Capital (%)					

Questionnaire continued

Plant Technical Data \ Plant Name & Location						Remarks
Energy Source	Price of Purchased Power/KWh					
	Type					
Maintenance Cost Per Year in Local Currency						
Operating Cost (total/yr) in Local Currency						
Total Fixed and Variable Cost (including maintenance)						
Cost Per Cubic Meter of Desalinated Brackish Water						

III. Please, indicate price charged to users per cubic metre:

(a) Household:

(b) Industry:

(c) Irrigation:

(d) Other (specify):

IV. Please, indicate if renewable energy is used in your brackish water desalination plants. Indicate how this affects costs per cubic metre of desalinated water (as a percentage):

V. Please, indicate if technical assistance is needed in:

(a) Brackish water investigation:

(b) Desalination technologies:

(c) Training:

VI. Additional remarks:

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